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Potential of applying adaptive strategies in buildings to reduce the severity of fuel poverty according to the climate zone and climate change: The case of Andalusia

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ABSTRACT

The reduction of fuel poverty is among the major challenges of countries, policymakers, stakeholders, and researchers. Many contributions have today emerged; however, two aspects should be widely considered. On the one hand, the use of strategies based on the reduction of energy consumption through the adaptive approach, and on the other hand, the impact of climate change on fuel poverty, particularly considering the recent representative concentration pathways (RCP). This paper addresses both issues in Andalusia, which is among the regions with the highest population ratio under poverty risk. For this purpose, 4 zones with possibilities of applying adaptive strategies were distinguished in the Andalusian geography, and 3 climate change scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) were projected in each decade (from 2030 to 2100). A total of 6,528 cases of representative social housing, simulated in all scenarios, were parametrically studied. All data were assessed from the point of view of fuel poverty risk. The results showed that the adaptive strategies influence the reduction of fuel poverty, both in annual and monthly values. Moreover, the increase in fuel poverty cases because of global warming could be reduced by this approach in the four zones detected in Andalusia.

1. Introduction

The energy performance of most buildings in Europe is deficient (Gangolells, Casals, Forcada, MacArulla, & Cuerva, 2016; Kurtz, Monzón, & López-Mesa, 2015), mainly because most of them were built before the implementation of the first standards on energy efficiency in the European countries (Semprini, Gulli, & Ferrante, 2017). Consequently, building energy consumption is high. In quantified data, buildings are responsible for both 40 % of energy consumption (European Commission, 2006; European Environment Agency, 2018) and 36 % of greenhouse gas emissions (European Commission, 2002; European Union, 2010). This situation, together with the economic precariousness of many European family units as a result of Lehman Brothers' economic crisis (de Haas & van Horen, 2012), has contributed to fuel poverty cases. Thus, many governments have established policies focused on defining, quantifying, and reducing fuel poverty. The ambiguity in the designation of this phenomenon also takes place in the concept itself: (i) fuel poverty related to the inability of family units to meet the major heating or cooling energy requirements in their dwellings (Bouzarovski & Petrova, 2015; Legendre & Ricci, 2015), and (ii) energy poverty is related to the difficulty of accessing to both energy supplies (Ayodele, Ogunjuyigbe, & Opebiyi, 2018; Bouzarovski, Petrova, & Tirado-Herrero, 2014) and appropriate installations (Bouzarovski & Petrova, 2015), an aspect mainly taking place in developing countries (Tarekegne, 2020). Nonetheless, both phenomena could take place; an excessive energy expenditure and the lack of liquidity of family units could lead to unpaid invoices and energy supply loss (Dagoumas & Kitsios, 2014).

For this reason, the establishment of mitigating policies is something of a challenge. In Spain, the government established the National Strategy against Energy Poverty 2019–2024, which was aimed to reduce fuel poverty cases between 25 and 50 % by 2025 in comparison with the data recorded in 2017 (The Government of Spain, 2019). For this purpose, quantifying fuel poverty is crucial. The Spanish national plan is based on the methodology established by the EU Energy Poverty Observatory (EPOV) to measure and quantify fuel poverty. Specifically, EPOV uses 4 indicators: high share of energy expenditure in income, low

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absolute energy expenditure, inability to keep home adequately warm, and arrears on utility bills. Thanks to these indicators, many casuistries related to fuel poverty are considered and can be established in various risk groups (Sánchez-Guevara Sánchez, Sanz Fernández, Núñez Peiró, & Gómez Muñoz, 2020). In general terms, these combinations are based on the combinations of incomes and energy expenditure by considering the threshold values of monetary and fuel poverty in each country (Sánchez-Guevara Sánchez et al., 2020). This could make difficult to assess certain fuel poverty cases related to very low energy expenditure that affects users' health. In this regard, many studies have determined that family units in fuel poverty could face many thermal discomfort hours (Shortt & Rugkåsa, 2007) which could lead to health problems or death (Liddell & Guiney, 2015; Middlemiss & Gillard, 2015; Thomson & Snell, 2013). Thus, measures to mitigate fuel poverty should be established to guarantee users' thermal comfort (Bouzarovski & Petrova, 2015; Legendre & Ricci, 2015). It is worth stressing that the major contribution of residential building energy consumption is the use of HVAC systems, beyond other consumption sources such as domestic hot water (Albertí et al., 2019) or electrical household appliances (Golmohamadi, Keypour, Bak-Jensen, & Radhakrishna Pillai, 2019). If consumption of HVAC systems was reduced, most fuel poverty cases would be reduced, as well. For this purpose, energy rehabilitation could be an option to reduce that consumption, particularly if climate conditions and the technical characteristics of the building contribute to high energy consumption (Vilches, Barrios Padura, & Molina Huelva, 2017). However, the high economic investment on the part of low-income family units (Healy & Clinch, 2004) and the rebound effects (Seebauer, 2018) could limit the effectiveness of energy rehabilitation to reduce fuel poverty. To guarantee an appropriate reduction of the consumption of HVAC systems, the main goal of users using these systems (i.e., to keep appropriate thermal comfort levels) should be considered (Montalbán Pozas, 2018; Vilches et al., 2017). This situation has been traditionally considered in the winter months (Healy, 2003; Healy & Clinch, 2002), although the thermal comfort problem is more and more extended to the summer months (Sánchez-Guevara Sánchez, Núñez Peiró, Taylor, Mavrogianni, & Neila González, 2019; Tabata & Tsai, 2020).

Measures to reduce energy consumption in hot and cold months should therefore be established, and the use of HVAC systems could be an appropriate measure. According to Ghose, McLaren, and Dowdell (2020), using resources appropriately is more important than other energy saving measures, such as self-consumption. Likewise, Gianfrate, Piccardo, Longo, and Giachetta (2017) determined that an appropriate operational pattern of HVAC systems could reduce the impact of fuel poverty. An appropriate use of HVAC systems should guarantee users' thermal comfort. For this reason, the potential of energy saving has been analysed by using adaptive thermal comfort strategies (Sánchez-García, Bienvenido-Huertas, Tristancho-Carvajal, & Rubio-Bellido, 2019). For this purpose, research works are based on the possibilities of reducing HVAC system energy consumption by adapting setpoint temperatures to the limits of adaptive models (Ren & Chen, 2018; Sánchez-García, Rubio-Bellido, Marrero Meléndez, Guevara-García, & Canivell, 2017; Sánchez-García, Rubio-Bellido, del Río, & Pérez-Fargallo, 2019), taking advantage of the potential of energy saving due to the rebound effect of setpoint temperatures (Parkinson, de Dear, & Brager, 2020). Thus, adaptive thermal comfort strategies consider the possibility of using adaptive setpoint temperatures, so individuals' thermal adaptability could be considered in view of outdoor climate variations. Some of the studies are as follows: (i) Sánchez-García, Bienvenido-Huertas, Tristancho-Carvajal et al. (2019); Sánchez-García, Rubio-Bellido, del Río et al. (2019) assessed in various Spanish cities the modification of the operational profile of the Spanish regulation by using adaptive setpoint temperatures. With these modifications, the energy consumption of the buildings analysed was saved between 10 and 46 % without making economic investments; (ii) Yun, Lee, and Steemers (2016) performed an application analysis of an adaptive thermal comfort model in the use of HVAC systems in office buildings in South Korea. An energy saving of up to 22 % was obtained; (iii) Sánchez-Guevara Sánchez, Mavrogianni, and Neila González (2017) analysed the application of monthly adaptive setpoint temperatures in 3 residential buildings in Avila, Madrid, and Seville (Spain). The energy saving ranged between 20 and 80 %; (iv) Bienvenido-Huertas, Rubio-Bellido, Farinha, Oliveira, and Pérez-Ordóñez (2020) analysed the application of adaptive setpoint temperatures in an office building located in the main cities of the Iberian Peninsula. Energy saving obtained by the adaptive strategies in the current and future scenarios (2050 and 2100) was greater with EN 16798-1:2019 than ASHRAE 55-2017.

Moreover, few studies related to fuel poverty have assessed the effectiveness of adaptive strategies. Bienvenido-Huertas, Sánchez-García, and Rubio-Bellido (2021) analysed the potential of reducing fuel poverty with adaptive setpoint temperatures in social housing in Seville. The analysis was performed according to data from 2015 and 2016. The results showed the great potential of reducing fuel poverty cases in the summer months. However, there are no other studies analysing the use of these strategies to reduce fuel poverty cases. In addition, fuel poverty has been scarcely studied throughout the 21 st century. In fact, some authors have reported, without quantifying it, that fuel poverty risk could be greater in the future. Roshan, Oji, and Attia (2019) indicated that, although the effects of fuel poverty in winter will be reduced by climate change, its increase in the hot months is foreseen.

Thus, climate change could strongly affect fuel poverty. This is a new aspect because many studies have reported the need for considering climate change when analysing buildings. In this regard, de Rubeis, Falasca, Curci, Paoletti, and Ambrosini (2020); Jalaei, Guest, Gaur, and Zhang (2020), and Chai, Huang, and Sun (2020) showed the importance of considering the impact of energy improvements throughout the useful life of the building. For this purpose, the impact of climate change on buildings due to the variation of environmental loads should be considered (Il Jeong & Sushama, 2018; Steenbergen, Koster, & Geurts, 2012). This is possible thanks to the climate evolution predictions made by the intergovernmental panel on climate change (IPCC). These scenarios have been changed throughout the years. The first group of scenarios were the special report on emissions scenarios (SRES) (Nakicenovic & Swart, 2000). These scenarios established 4 main groups (A1, A2, B1, and B2) which have been related to climate change in most studies because of the ease to generate climate data with them (Berardi & Jafarpur, 2020; Herrera et al., 2017). Some studies related to the impact of SRES on building energy performance are as follows: (i) Ciancio et al. (2020) analysed the impact of the A2 scenario on the energy consumption of residential buildings located in 19 European cities. The results showed that in 2080 in absolute values cooling energy consumption will be more increased than the reduction of heating energy consumption, with greater impact in the regions in the south of Europe; (ii) Gercek and Durmuş Arsan (2019) analysed the optimization of the design decision-making of a residential building in Turkey, considering the climate evolution of the SRES scenarios in 2020, 2050 and 2080; (iii) Jiang, Liu, Czarnecki, and Zhang (2019) developed the future weather file generator to obtain climate files of B1, B2, A2 and A1FI in 2,100 locations; (iv) Invidiata and Ghisi (2016) assessed passive design strategies, such as solar protection, low absorptance and thermal insulation, in Brazil in 2020, 2050 and 2080. Heating demand was reduced by 94 %; and (v) Xu, Huang, Miller, Schlegel, and Shen (2012) used four scenarios (A1F1, A2M, B1 and B2M) to assess the impact on the energy demand of buildings located in California in 2040, 2070 and 2100. Cooling energy demand increased by 50 %.

However, the SRES scenarios were modified by IPCC through the representative concentration pathways (RCP) scenarios (Scott, Hall, & Gossling, 2016). The RCP scenarios establish four evolution tendencies of the greenhouse gas emissions throughout the 21st century: an strict reduction scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0), and an scenario with very high greenhouse gas emissions (RCP 8.5). These scenarios are not widely used to study the evolution of energy performance and thermal comfort; however, few studies have analysed them: (i) Zhai and Helman (2019) analysed the variation of energy performance in 5 representative buildings of the University of Michigan. The results showed an increase by up to 90 % in cooling energy consumption in RCP 8.5; (ii) Aminipouri et al. (2019) assessed the possibility of using trees to improve the outdoor thermal comfort in Vancouver in the RCP scenarios. The results showed that the use of trees reduced the average radiant temperature by 1.3 °C in RCP 4.5, but this temperature was not reduced in RCP 8.5; (iii) Roshan et al. (2019) analysed the influence of the RCP scenarios on residential buildings in Iran. The results showed the future need for cooling bioclimatic passive strategies in the buildings of the region, together with the use of passive solar heating; (iv) Verichev, Zamorano, and Carpio (2020) analysed in the south of Chile the effect of RCP 2.6 and RCP 8.5 on the buildings designed with the current construction standard. The results showed that future conditions (mainly characterized by a lower heating demand) will imply that the design criteria established by the Chilean standard are not valid in the future; (v) Kikumoto, Ooka, Arima, and Yamanaka (2015) assessed the increase in the total sensible load inside a building in RCP 4.5 in 2030. The sensible heat load was increased by 15 % under the conditions considered; and (vi) Cellura, Guarino, Longo, and Tumminia (2018) assessed with the RCP scenarios the impact of climate change on the building stock. The results showed that climate change will worsen the current and usual problems of high building performance, such as overheating, and increase cooling energy consumption in Europe.

Thus, climate change is expected to change the impact of fuel poverty throughout the 21 st century, thus affecting the design of mitigating policies. As established by da Guarda et al. (2020), the energy analysis implies to know also in the future the possible effectiveness of the energy policies today adopted. Having data on the future tendency of fuel poverty in view of the climate variation could therefore provide greater information to establish policies (Gürdür Broo et al., 2021; (Ola) Michalec, Hayes, & Longhurst, 2019).

For this reason, this research assesses how RCP scenarios will affect fuel poverty throughout the 21st century and analyses the effectiveness of the adaptive strategies. Thus, a new approach is provided to analyse fuel poverty; this new approach is based on considering the future impact of RCP scenarios (Siksnelyte-Butkiene, Streimikiene, Lekavicius, & Balezentis, 2021). In addition, the use of RCP scenarios in relation to energy performance should be widely studied. Likewise, aspects hardly discussed in the scientific literature are suggested, such as the influence of the families' purchasing power, climate change, and fuel poverty. The key contributions of this paper can therefore be summarized as follows:

- Characterization of fuel poverty in the current scenario (2015, 2016, and 2017) in the building stock in the south of Spain.
- Analysis of fuel poverty in the context of the RCP scenarios (2.6, 4.5, and 8.5) throughout the 21 st century (2030-2100).
- Influence of the use of adaptive setpoint temperatures on HVAC systems to reduce fuel poverty in current and future scenarios.
- Impact of the analysis scale (annual and monthly) on the assessment of fuel poverty.
- Influence of family income levels on the evolution of fuel poverty throughout the 21 st century.

For this purpose, a parametric process was carried out to generate many case studies, which were located in 4 zones to apply the adaptive thermal comfort models in Andalusia (Spain) (Bienvenido-Huertas, Rubio-Bellido, Farinha et al., 2020). Andalusia was selected because of the high impact of fuel poverty in the region (Llorca, Rodriguez-Alvarez, & Jamasb, 2020). The Spanish Institute of Statistics reflected that the Andalusian autonomous community has the highest population ratio under poverty risk, being 13.1 % greater than the nation value in 2016 (European Commission, 2014). On the other hand, the report by the Environmental Science Association showed that the Andalusian population with income levels lower than the limit considered in 2014 was greater between 3 and 10 % than the national mean; moreover, this autonomous community was among those with the most unfavourable values (Tirado Herrero et al., 2016). In addition, the climate characteristics in many zones of the region are similar to those of other European cities in the Mediterranean region (Bienvenido-Huertas, Sánchez-García, & Rubio-Bellido, 2020), so the results could be extrapolated to other regions.

2. Methodology

2.1. Adaptive thermal comfort model of EN 16798-1:2019 and application zones in Andalusia

Adaptive thermal comfort models are among the models with greater potential of energy saving (Sánchez-García, Rubio-Bellido, del Río et al., 2019). These models are based on individuals' thermal adaptation capacity in relation to the usual climate variations daily produced. Thus, the limits of adaptive thermal comfort could vary in the summer months according to the values of the outdoor temperature in the previous days. This type of thermal comfort models has been widely developed in standards from the end of the 20th century to nowadays (Carlucci, Bai, de Dear, & Yang, 2018; Karyono, Abdullah, Cotgrave, & Bras, 2020), and in studies that have developed specific models for certain regions (Manu, Shukla, Rawal, Thomas, & de Dear, 2016; Udrea, Croitoru, Nastase, Crutescu, & Badescu, 2018; Williamson & Daniel, 2020), so there is a clear interest in these models. The most important standards for their development and application scope are the American standard (ASHRAE 55-2017 (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) (2017)) and the European standard (EN 16798-1:2019 (European Committee for Standardization, 2019)). ASHRAE 55 emerged before including the adaptive thermal comfort model because a static thermal comfort model based on Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) was available (Fanger, 1970). However, data compiled through the ASHRAE RP-884 project (Carlucci et al., 2018) and based on the studies by de Dear and Brager (2001, 2002) were included in 2004. The first version of the European standard was included in EN 15251:2007 (European Committee for Standardization, 2007), which was recently reviewed by EN 16798-1:2019 (European Committee for Standardization, 2019). The adaptive thermal comfort model included in this standard was developed through the smart controls and thermal comfort (SCATs) Project (McCartney & Nicol, 2002) and can be applied in European countries. In this study, the adaptive thermal comfort model included in the European standard was used because it was applied in case studies of the continent, similarly to other studies on the application of adaptive models in the continent (Bienvenido-Huertas, Sánchez-García, Rubio-Bellido et al., 2020).

The EN 16798-1:2019 standard establishes 3 categories for the adaptive thermal comfort model: Category I for vulnerable users or users with low thermal adaptation; Category II to be applied in new buildings, and Category III to be applied in existing buildings. Each category establishes upper and lower limits among which the operative temperature should oscillate. The categories define the existing amplitude between upper and lower limits, so the narrowest range belongs to Category I, and the widest range belongs to Category III. To determine the limits, the running mean outdoor temperature (T_{rm}) should be previously determined. This variable determines the variation of the outdoor temperature and is calculated through the weighted sum of the outdoor mean temperature of the previous days (Eq. (1)). The value used for α could strongly influence both the determination of this variable and the effectiveness of using the adaptive model (Bienvenido-Huertas, Sánchez-García, Pérez-Fargallo, & Rubio-Bellido, 2020), so the criteria and recommendations established by the standards should be considered. EN 16798-1: 2019 recommends using a value of 0.8. With T_{rm}, two aspects of adaptive thermal comfort models could be determined:

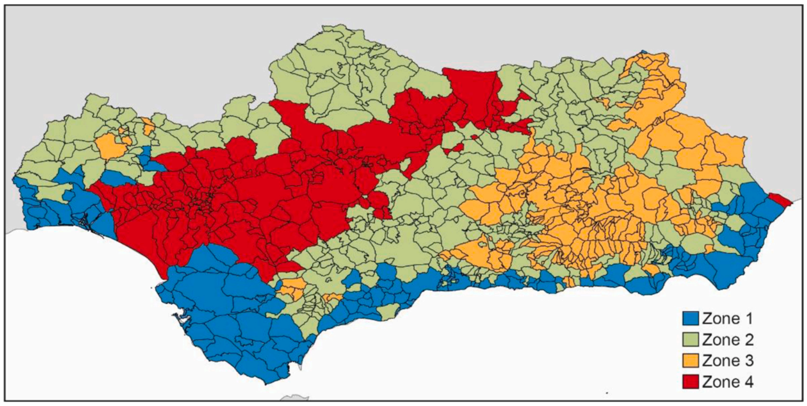

Fig. 1. Zones to apply the adaptive strategies in Andalusia.

- If the adaptive model could be applied. For this purpose, EN 16798-1:2019 establishes that T_{rm} should oscillate between 10 and 30 °C.
- The determination of the upper and lower limit values. Each category has linear correlations with respect to T_{rm} that determine the upper and lower limit value. Eqs. (2)–(7) includes the linear correlations of the upper and lower limits of each category.

$$T_{rm} = (T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7})/3.8 \; [°C] \quad (1)$$

$$Upper\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 20.8\ [°C] \quad (10 \le T_{rm} \le 30) \quad (2)$$

$$Lower\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 15.8\ [°C] \quad (10 \le T_{rm} \le 30) \quad (3)$$

$$Upper\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 21.8\ [°C] \quad (10 \le T_{rm} \le 30) \quad (4)$$

$$Lower\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 14.8\ [°C] \quad (10 \le T_{rm} \le 30) \quad (5)$$

$$Upper\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 22.8\ [°C] \quad (10 \le T_{rm} \le 30) \quad (6)$$

$$Lower\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 13.8\ [°C] \quad (10 \le T_{rm} \le 30) \quad (7)$$

Thus, the categories of EN 16798-1:2019 vary the limit values, and users' thermal comfort demands could be adapted to outdoor climate variations. However, the requirements and recommendations established in the national policies could not consider this type of users' thermal adaptation in the operational patterns. In Spain, the Spanish Building Technical Code considers a static thermal comfort model (The Government of Spain, 2006). In this model, the upper and lower limit values do not vary according to the oscillations of the outdoor temperature. The only aspect that varies is the hour of the day: (i) in periods of heating demand, the lower limit is 20 °C during the day and 17 °C at night, and (ii) in periods of cooling demand, the upper limit is 25 °C during the day and 27 °C at night. This implies that the possibilities of users' adaptation are not considered. Several studies have discussed the possible limitations in terms of energy saving by considering a static operational pattern (Sánchez-García, Bienvenido-Huertas, Pulido-Arcas, & Rubio-Bellido, 2020; Sánchez-García, Bienvenido-Huertas, Tristancho-Carvajal et al., 2019; Sánchez-García, Rubio-Bellido, del Río et al., 2019). In this regard, one of the energy saving strategies with adaptive models is the use of adaptive setpoint temperatures. These adaptive setpoint temperatures are adapted to the upper and lower limit values of the adaptive model. When T_{rm} is lower than 10 °C or greater than 30 °C, the value of the thermal comfort limits in the corresponding threshold is used as the adaptive setpoint temperature (e.g., for a T_{rm} of 9 °C, the limits in 10 °C would be used). This contributes to the energy saving by the rebound effect of the setpoint temperatures (Parkinson et al., 2020) by reducing building energy demand. The use of these strategies is of great potential in most parts of the Earth (Bienvenido-Huertas, Rubio-Bellido, Farinha et al., 2020). In Andalusia, a recent study analysed the potential of applying adaptive models and using adaptive setpoint temperatures with climate data recorded from the mid-20th century to today (Bienvenido-Huertas, Rubio-Bellido, Farinha et al., 2020). In addition, a classification analysis of the cities in the region was applied by identifying four zones with possibilities of application according to four factors: (i) the percentage of days of the year when the model can be applied, (ii) the annual percentage of ventilation hours, (iii) the saving in heating degrees, and (iv) the saving in cooling degrees. Briefly summarised, the characteristics of each zone are as follows: (i) zone 1 corresponds to coastal cities whose energy demand is low with static patterns, thus implying a lower effectiveness of the adaptive strategies. However, the possibility of applying adaptive models is almost 100 % of the days of the year; (ii) zone 2 corresponds to cities located in mountain ranges in Andalusia (e.g., Sierra Morena). This zone is related to high heating and cooling energy demands, so the use of the adaptive model could obtain significant savings; (iii) zone 3 corresponds to most cities located in the zones with the greatest altitude in the Baetic Systems (e.g., Sierra Nevada), which are characterised by having the greatest heating energy demand; and (iv) zone 4 corresponds to the cities located in the Guadalquivir Depression that are characterised by having the greatest cooling energy demand, together with a moderate heating demand (Fig. 1).

2.2. Climate data used in this study

The application of the adaptive setpoint temperatures and their effect on the reduction of fuel poverty cases, both today and throughout the 21st century, are different in the various periods. For this reason, the four application zones were analysed both the in the current and climate change scenarios. The assessment of fuel poverty in both the current and future scenario should be analysed to know the variations expected throughout the 21st century. Thus, measures could be establish to take actions in advance and to avoid the vulnerability of families. In addition, these analyses between various scenarios and the establishment of building energy saving measures are expected to reduce not only possible cases of fuel poverty but the evolution of climate change (Ürge-Vorsatz & Tirado Herrero, 2012). A city representing each zone was selected. Each city obtained climate data for the current and climate change scenarios. As for the current scenario, hourly data of the climate in each city in 2015, 2016 and 2017 were obtained (these data were recorded by the State Meteorological Agency in Spain (AEMET in Spanish). AEMET has automatic weather stations recording data, and

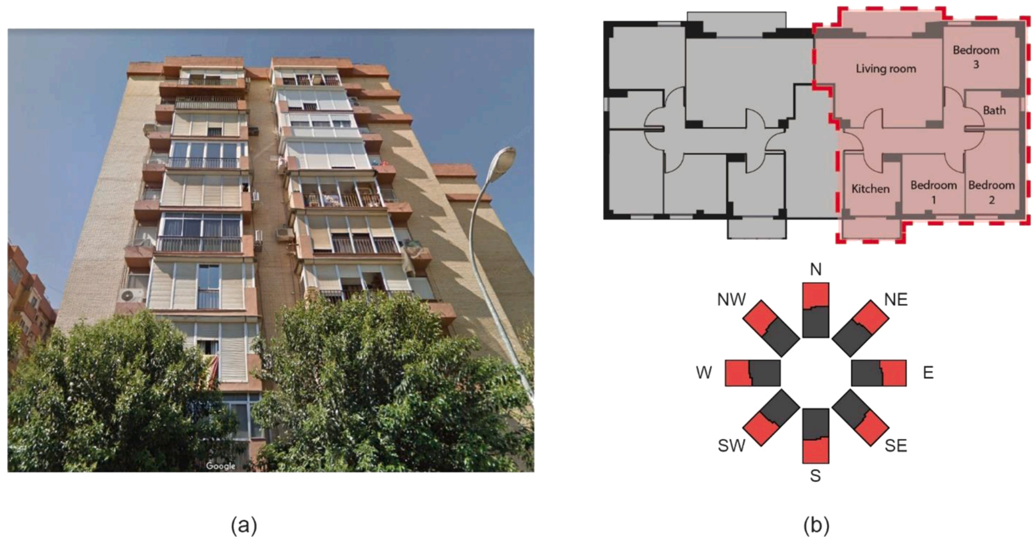

Fig. 2. Case study selected to design the parametric models: (a) photograph of the case study, and (b) distribution and orientation of the dwelling.

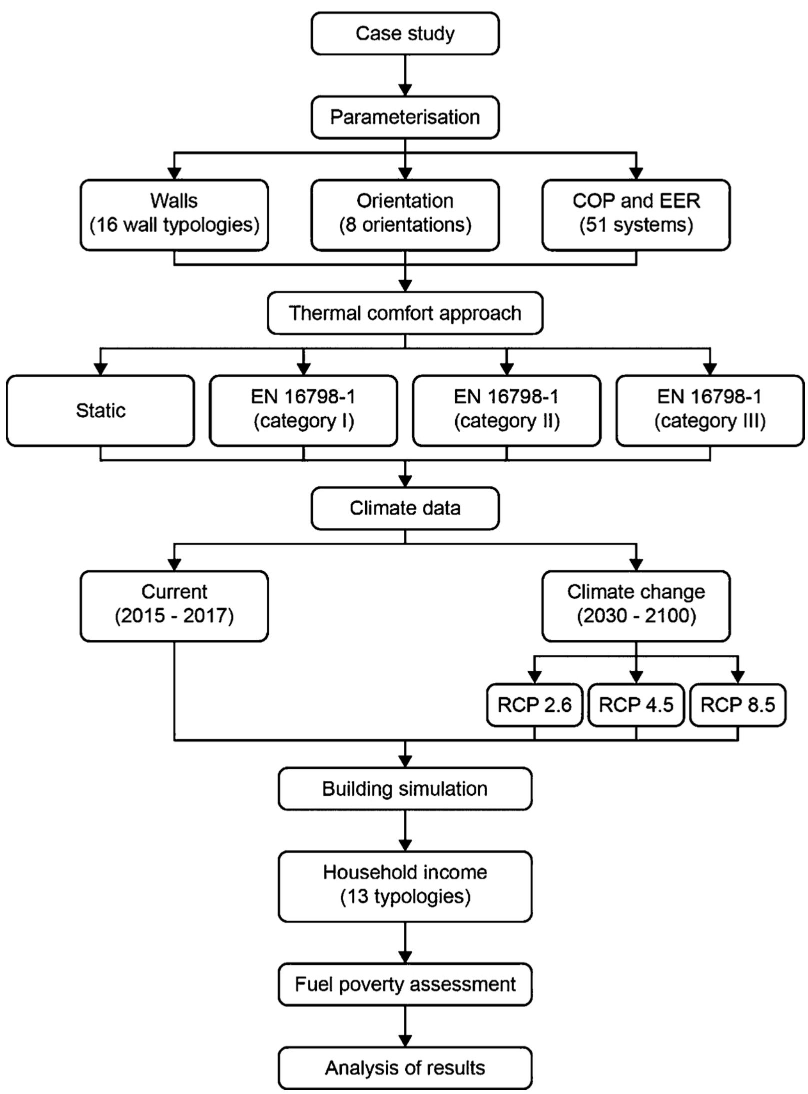

Fig. 3. Flowchart of the research.

Table 1
Types of walls considered in the research.

Wall	Layer	s [m]	λ W/mK]	U [W/(m²K)]
Wall 1	Cement mortar	0.015	1.300	3.087
	Solid brick	0.115	0.991	
	Gypsum plaster	0.010	0.570	
Wall 2	Cement mortar	0.015	1.300	2.037
	Hollow brick	0.060	0.212	
	Gypsum plaster	0.010	0.570	
Wall 3	Cement mortar	0.015	1.300	2.268
	Solid brick	0.240	1.030	
	Gypsum plaster	0.010	0.570	
Wall 4	Cement mortar	0.015	1.300	2.355
	Concrete block	0.200	0.923	
	Gypsum plaster	0.010	0.570	
	Cement mortar	0.015	1.300	1.225 [a]
	Hollow brick	0.060	0.212	1.196 [b]
Wall 5	Air gap	–	–	1.182 [c]
	Hollow brick	0.040	0.228	
	Gypsum plaster	0.015	0.570	
	Cement mortar	0.015	1.300	1.540 [a]
	Solid brick	0.115	0.991	1.494 [b]
Wall 6	Air gap	–	–	1.472 [c]
	Hollow brick	0.040	0.228	
	Gypsum plaster	0.015	0.570	
	Cement mortar	0.015	1.300	1.305 [a]
	Solid brick	0.240	1.030	1.272 [b]
Wall 7	Air gap	–	–	1.256 [c]
	Hollow brick	0.040	0.228	
	Gypsum plaster	0.015	0.570	
	Cement mortar	0.015	1.300	1.695 [a]
	Solid brick	0.115	1.030	1.639 [b]
Wall 8	Air gap	–	–	1.613 [c]
	Solid brick	0.115	1.030	
	Gypsum plaster	0.015	0.570	

[a] Air gap de 1 cm.
[b] Air gap de 2 cm.
[c] Air gap de 3 cm.

these data are then validated by AEMET. The available weather stations are as follows: in Cadiz (zone 1) and Jaen (zone 2), Thies 1.1005.54.700 is used (measurement range between -30 and 70 °C); in Grazalema (zone 3), Thies 1.1005.51.015 is used (measurement range between -30 and 50 °C); and in Seville (zone 4), VAISALA HMP45D is used (measurement range between -40 and 60 °C). The Energyplus weather (EPW) files used in the simulation process of the case studies were generated with the climate data obtained between 2015 and 2017, thus generating a total of 3 EPW files (2015, 2016 and 2017) in each zone for the current scenario.

As for the climate data throughout the 21st century, data were obtained with METEONORM, a database of climate files composed of 8,325 weather stations distributed all over the world which is widely used (Bellia, Pedace, & Fragliasso, 2015; Hatwaambo, Jain, Perers, & Karlsson, 2009; Kameni et al., 2019; Osman & Sevinc, 2019). However, METEONORM is not just a meteorological database; it also allows spatial interpolations to be made to generate stochastic meteorological data (Yassaghi, Mostafavi, & Hoque, 2019).

The scenarios used were the representative concentration pathways (RCP). A total of 3 scenarios with a different climate change severity level were used: RCP 2.6 (low), RCP 4.5 (medium), and RCP 8.5 (high). These scenarios consider various evolution tendencies of the greenhouse gas emissions included in the IPCC 2014 report (Intergovernmental Panel on Climate Change, 2014). It is estimated that, by the end of the 21 st century, the global mean temperature will increase between 0.3 and 1.7 °C in RCP 2.6, between 1.1 and 2.6 °C in RCP 4.5, and between 2.6 and 4.8 °C in RCP 8.5. Thus, RCP 2.6 is the scenario closer to the goal established in the Paris Agreement (an increase in the medium surface temperature of 1.5 °C in comparison with the preindustrial levels) (Masson-Delmotte et al., 2018), with both a high increase in the temperature and serious effects on the habitat (Intergovernmental Panel on Climate Change, 2014). METEONORM includes the RCP 2.6, 4.5 and 8.5 scenarios from 10 global climate models based on an average of a selection from the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor, Stouffer, & Meehl, 2012). The Global Circulation Models (GCMs) used for METEONORM are as follows (METEONORM, 2019): ACCESS1-0_r1i1p1, ACCESS1-3_r1i1p1, CMCC-CM_r1i1p1, CNRM-CM5_r1i1p1, HadGEM2-CC_r1i1p1, HadGEM2-ES_r1i1p1,

Table 4
Various types of incomes considered in the study according to the IPREM.

Factor applied to the IPREM	Family unit's monthly income [€/month]
0.50	313.32
0.75	469.97
1.00	626.63
1.25	783.29
1.50	939.95
1.75	1,096.60
2.00	1,253.26
2.25	1,409.92
2.50	1,566.58
2.75	1,723.23
3.00	1,879.89
3.25	2,036.55
3.50	2,193.21

Table 2
Percentage distribution of loads in the energy simulation processes.

Loads		Period					
		0:00–6:59	7:00–14:59	15:00–17:59	18:00–18:59	19:00–22:59	23:00–23:59
Occupancy	Weekdays	100	25	50	50	50	100
	Weekend	100	100	100	100	100	100
Equipment and lighting	Weekdays and weekend	10	30	30	50	100	50

Table 3
Operational approaches of the HVAC systems considered in the study.

Model	Category	Setpoint temperature			
		Upper limit		Lower limit	
		0:00–06:59	07:00–23:59	0:00–06:59	07:00–23:59
Static		27	25	17	20
Adaptive	Category I	Eq. (2)	Eq. (2)	Eq. (3)	Eq. (3)
	Category II	Eq. (4)	Eq. (4)	Eq. (5)	Eq. (5)
	Category III	Eq. (6)	Eq. (6)	Eq. (7)	Eq. (7)

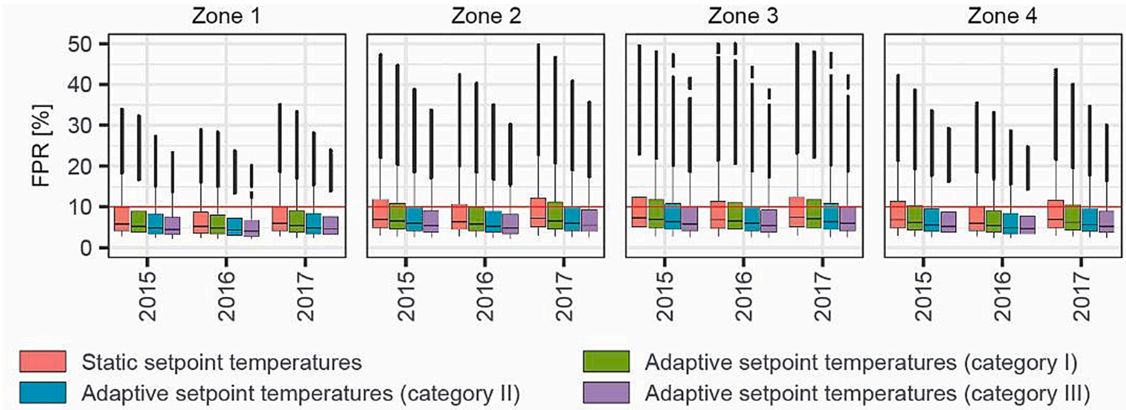

Fig. 4. Distribution of the annual FPR values in the current scenario according to the type of operational pattern.

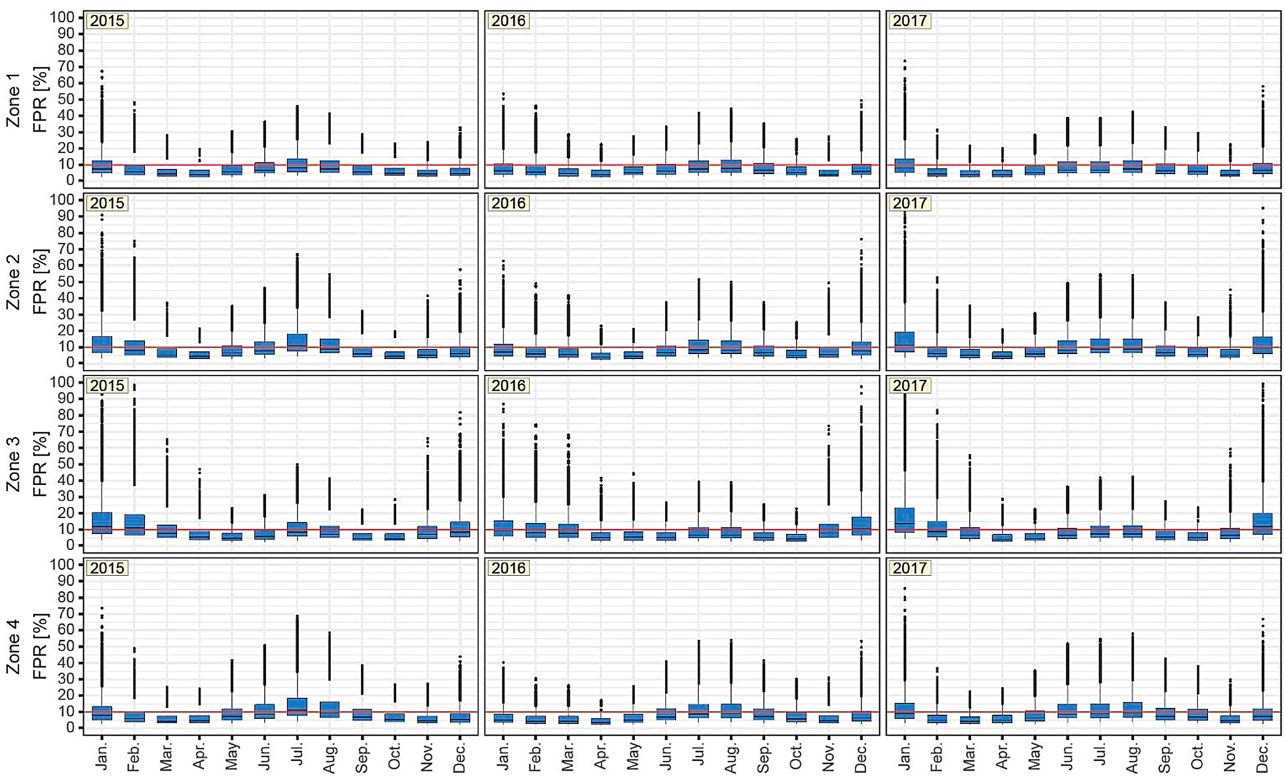

Fig. 5. Distribution of the monthly FPR values in the current scenario using static patterns.

Table 5
Percentage decrease with the use of adaptive patterns of the FPR distribution values in comparison with those obtained with static operational patterns.

Period	Zone	Percentage decrease (%)														
		Category I					Category II					Category III				
		Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max
Annual	Zone 1	0.23	0.36	0.51	0.80	1.30	0.33	0.67	0.95	1.63	6.25	0.37	0.90	1.27	2.27	10.20
	Zone 2	0.24	0.41	0.55	0.95	2.61	0.38	0.78	1.12	1.89	8.23	0.48	1.11	1.60	2.70	13.24
	Zone 3	0.13	0.24	0.31	0.54	1.10	0.27	0.63	0.91	1.48	7.34	0.38	0.97	1.44	2.29	12.97
	Zone 4	0.27	0.44	0.62	1.04	3.13	0.40	0.78	1.12	1.89	8.11	0.49	1.07	1.51	2.59	12.43
January	Zone 1	−0.05	−0.22	−0.37	−0.67	−6.89	0.12	0.35	0.54	0.93	4.28	0.23	0.84	1.37	2.34	14.88
	Zone 2	0.02	0.00	0.02	−0.02	−1.68	0.22	0.52	0.99	1.68	8.87	0.39	1.04	1.89	3.28	19.19
	Zone 3	−0.01	−0.05	−0.08	−0.14	−1.54	0.23	0.49	0.97	1.65	9.51	0.47	1.03	2.01	3.45	20.44
	Zone 4	0.02	−0.01	−0.05	−0.05	−2.89	0.17	0.48	0.80	1.41	7.31	0.28	0.92	1.53	2.68	16.90
August	Zone 1	0.70	1.10	1.56	2.66	9.96	0.87	1.49	2.11	3.57	12.83	0.95	1.83	2.58	4.32	15.61
	Zone 2	0.61	1.00	1.41	2.45	10.32	0.82	1.41	1.99	3.42	14.50	1.04	1.80	2.55	4.36	18.24
	Zone 3	0.54	0.84	1.18	2.04	7.82	0.67	1.19	1.67	2.88	10.67	0.74	1.49	2.12	3.57	13.27
	Zone 4	0.60	0.98	1.38	2.41	10.06	0.82	1.40	1.97	3.40	14.36	1.04	1.80	2.55	4.38	18.54

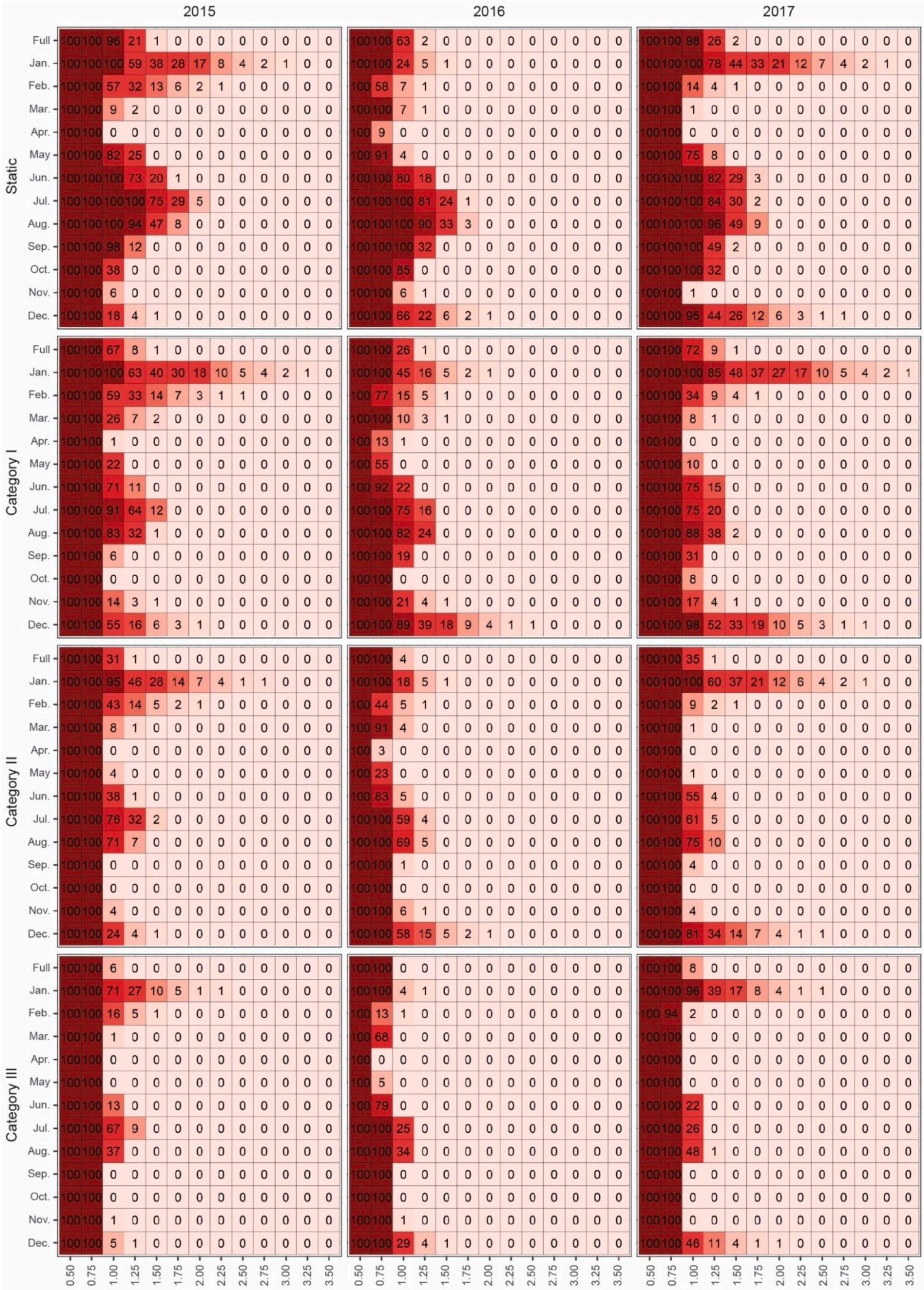

Fig. 6. Percentage of fuel poverty cases located in zone 1 in the current scenario.

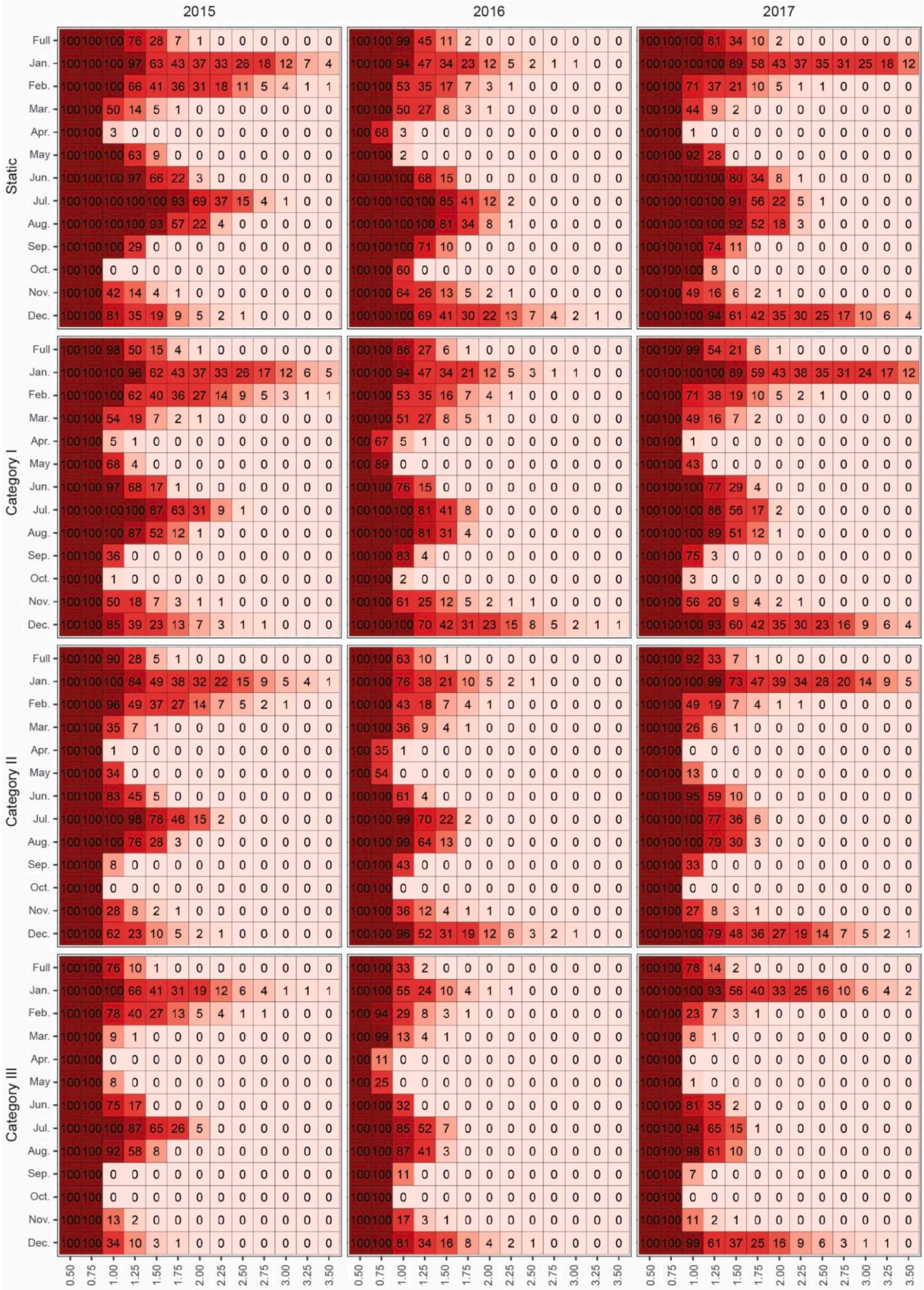

Fig. 7. Percentage of fuel poverty cases located in zone 2 in the current scenario.

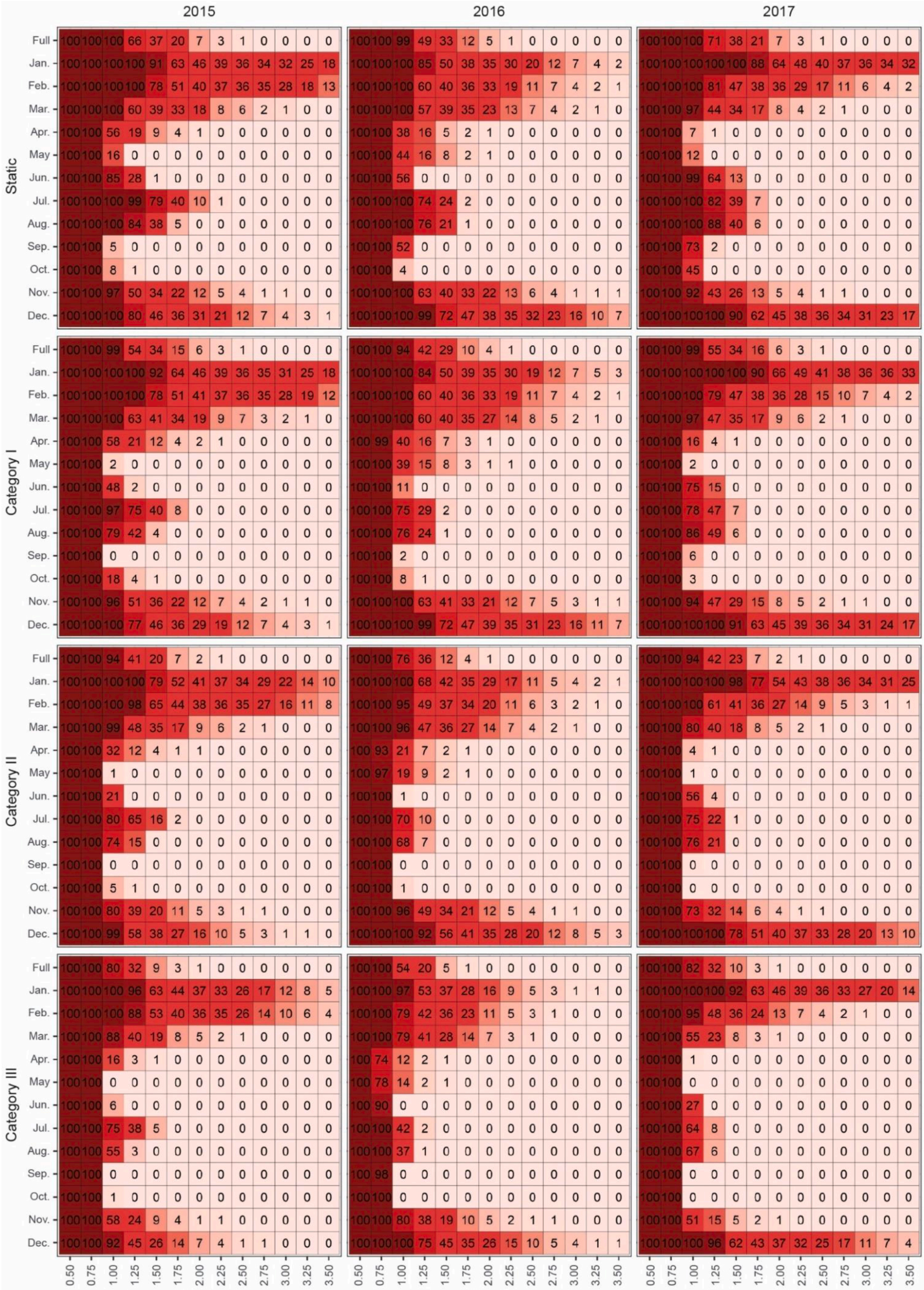

Fig. 8. Percentage of fuel poverty cases located in zone 3 in the current scenario.

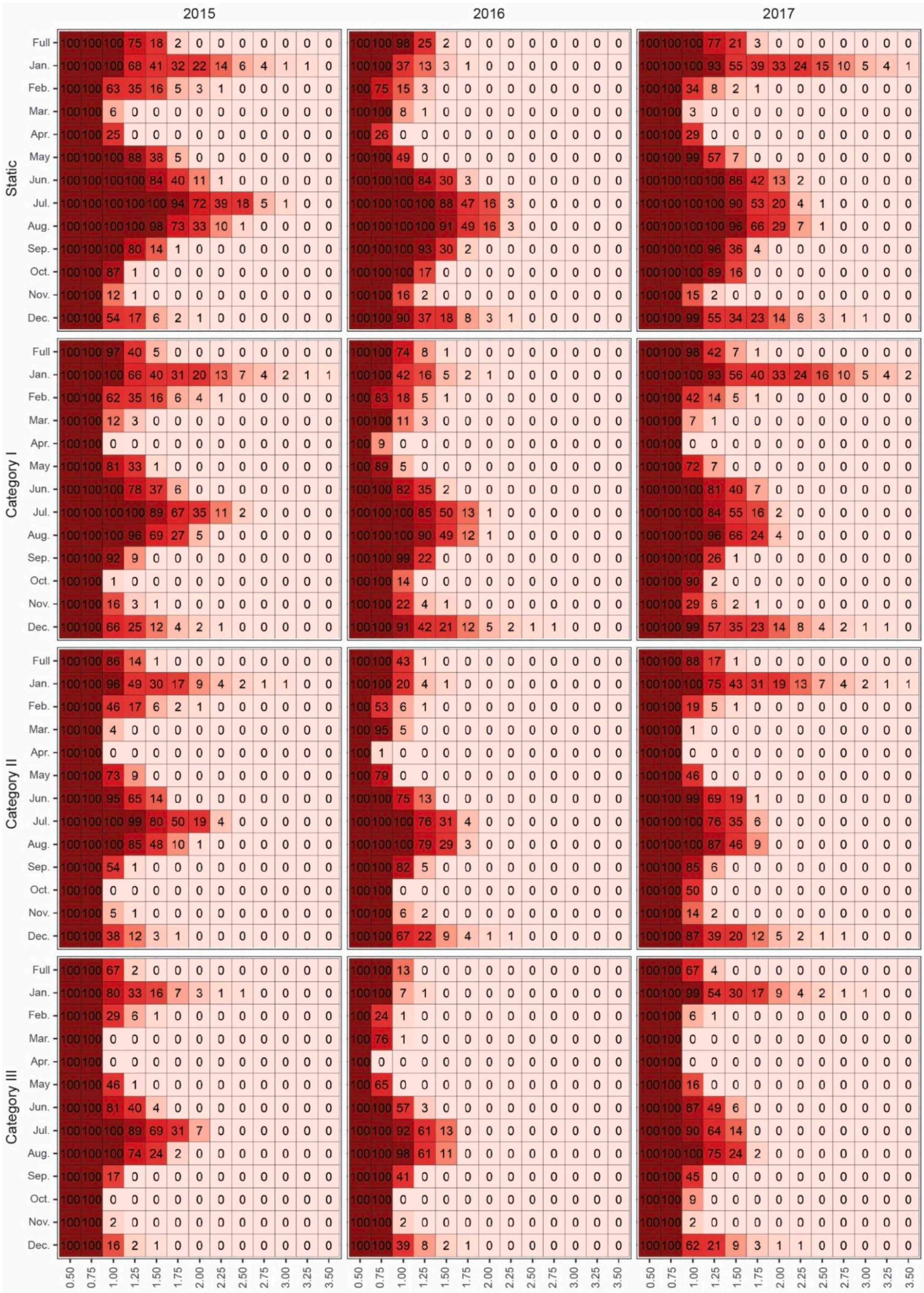

Fig. 9. Percentage of fuel poverty cases located in zone 4 in the current scenario.

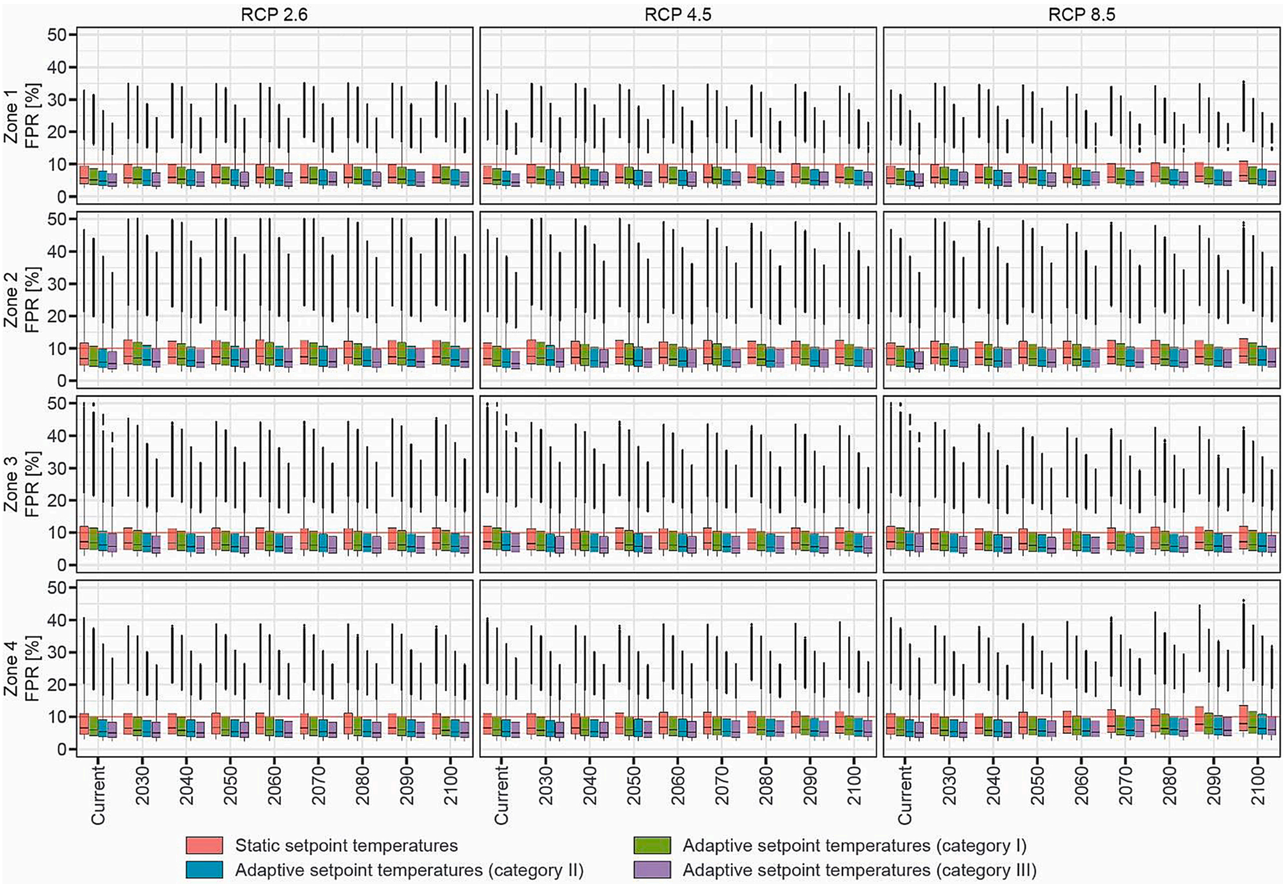

Fig. 10. Distribution of the annual FPR values from 2030 to 2100 according to the type of operational pattern.

HadGEM2-ES_r2i1p1, HadGEM2-ES_r3i1p1, HadGEM2-ES_r4i1p1, and IPSL-CM5A-MR_r1i1p1. These 10 GCMs were selected because of the greatest adjustment with the variables that the software uses. The models used are averaged for the periods 2011-2030, 2046-2065, and 2080-2099. Through linear interpolations, METEONORM allows the values of each decade of the 21 st century to be obtained. Thus, each scenario (RCP 2.6, 4.5, and 8.5) obtained the climate data corresponding to the decades of the 21st century after conducting this study (i.e., 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100). A total of 8 EPW files were obtained by each RCP in each zone, so each location obtained 24 EPW files.

2.3. Case studies

The goal of the study is the analysis of the potential to reduce fuel poverty throughout the 21 st century in the existing social housing building stock (as long as the building stock has not been completely renovated), so many case studies are required. For this purpose, a social housing model representing the building stock in Andalusia was selected, and a parametric process was carried out to obtain a greater variety of case studies. Some aspects of the actual case study are worth to be stressed before describing the parametrisation and simulation process (Fig. 2). The case study corresponds to a dwelling built before implementing the first standard on energy efficiency in the country (The Government of Spain, 1979), so its energy performance is very deficient (Kurtz et al., 2015). This type of dwellings constitutes the greatest percentage of the dwellings existing in Andalusia (Spanish Institute of Statistics, 2011). The surface of the dwelling is 65 m2, also representing the most existing type of surface in these buildings (Domínguez-Amarillo, Sendra, & Oteiza, 2016). A parametric process was carried out to obtain a great variety of case studies (Fig. 3). Firstly, concepts related to the orientation and the envelope were applied: 8 orientations were considered for the dwelling (Fig. 2(b)) as well as 16 typologies of different walls (Table 1). These 16 typologies of walls were obtained through 8 wall base designs whose air gap's thickness was modified according to the building construction techniques in Andalusia (Domínguez-Amarillo et al., 2016; Fernández-Agüera, Domínguez-Amarillo, Sendra, & Suárez, 2016). The 16 types of walls were selected according to their importance in the building stock of the region. Most of the existing buildings in the region correspond to the post-war construction period. This type of wall was characterized by no using insulating material as there was no energy efficiency standard (Kurtz et al., 2015). Thus, buildings with this type of envelope generally have worse energy performance (Kurtz et al., 2015). Although insulating material was incorporated in later construction periods, its importance in the building stock is not as significant as the envelope without insulating material (Spanish Institute of Statistics, 2011). In addition, the low rate of energy rehabilitation in the region suggests that the envelope of these buildings could not be improved (Ortiz & Salom, 2019). Thus, a total of 128 different models of case studies were obtained in relation to façade orientation and design. Each model had a model of heat pump for cooling and heating as this is the most usual system in Andalusia (Feijó-Muñoz et al., 2019). Equipment performance influences both energy consumption and fuel poverty impact, so 51 various equipment were considered by varying the indexes of Coefficient of Performance (COP) and Energy Efficiency Ratio (EER). This wide variety of performances allowed both old models with poor performance and recent models to be analysed. In this regard, users in these regions acquire recent heat pump models due to the useful life of these systems (D'Agostino, Mele, Minichiello, & Renno, 2020). By combining the types of HVAC systems, cases were in total 6,528.

Each case went through an energy simulation process by using the

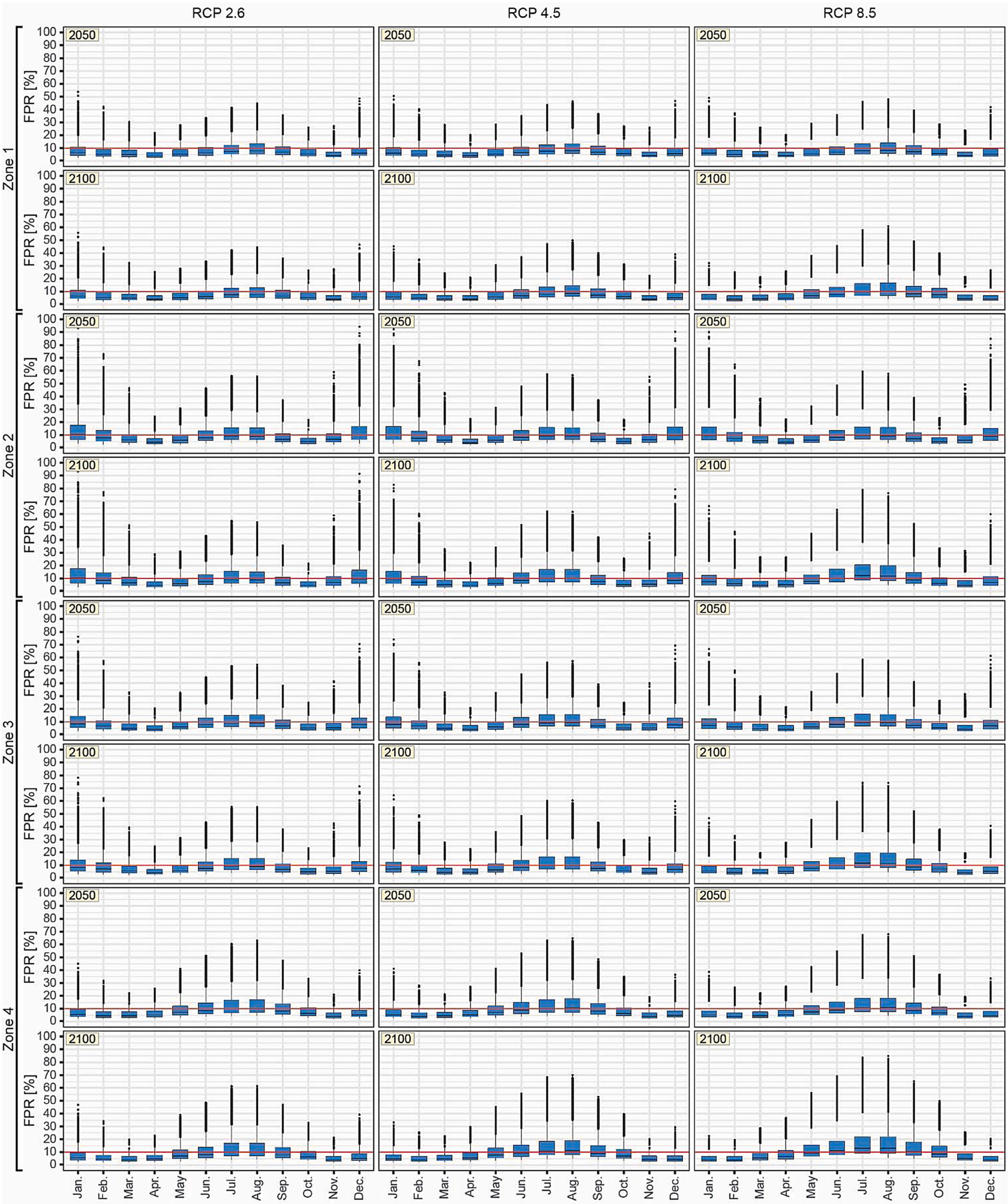

Fig. 11. Distribution of the monthly FPR values from 2050 to 2100 using static patterns.

EPW files described in Section 2.2. The simulation process was conducted with the load profile included in the Spanish Building Technical Code (Table 2), which represents the usual profiles of the residential housing in Spain. The use of this profile is appropriate as it is the standardized profile for the building energy analysis processes in Spain. This profile was characterised by the variation of the load values according to the type and the hour of the day: the occupancy load profiles varied according to the day of the week (weekdays or weekends), whereas the equipment or lighting systems load profiles were the same. A percentage value was applied to each hour with respect to the maximum load value that could take place in each type. These maximum values (corresponding to 100 %) of each load were as follows: 2.15 W/m^2 for the occupancy sensible load, 1.35 W/m^2 for the occupancy latent load, and 4.4 W/m^2 for the equipment and lighting system load.

As for the setpoint temperatures of HVAC systems, both a static operation pattern and an adaptive pattern were used. The static

Table 6
Percentage decrease by using adaptive patterns of the annual FPR distributions values in comparison with those obtained with static operational patterns.

Scenario	Zone	Percentage decrease (%)														
		Category I					Category II					Category III				
		Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max
RCP 2.6	Zone 1	0.22	0.35	0.49	0.75	1.17	0.33	0.70	0.99	1.66	6.52	0.39	0.95	1.36	2.42	10.81
	Zone 2	0.20	0.33	0.44	0.74	2.05	0.37	0.76	1.08	1.84	7.84	0.48	1.08	1.56	2.63	12.69
	Zone 3	0.23	0.38	0.52	0.90	2.36	0.36	0.75	1.04	1.75	7.99	0.49	1.10	1.57	2.61	13.26
	Zone 4	0.31	0.49	0.69	1.18	3.17	0.43	0.83	1.16	1.99	8.04	0.53	1.10	1.54	2.70	12.11
RCP 4.5	Zone 1	0.26	0.40	0.57	0.91	1.79	0.37	0.74	1.05	1.79	6.91	0.43	0.99	1.41	2.49	10.98
	Zone 2	0.22	0.35	0.47	0.81	2.11	0.39	0.78	1.11	1.88	7.97	0.49	1.09	1.57	2.64	12.62
	Zone 3	0.25	0.41	0.57	0.96	2.68	0.37	0.75	1.05	1.76	7.78	0.50	1.09	1.56	2.62	12.83
	Zone 4	0.34	0.54	0.77	1.31	3.86	0.47	0.87	1.22	2.09	8.51	0.57	1.12	1.57	2.75	12.28
RCP 8.5	Zone 1	0.31	0.51	0.71	1.18	2.98	0.42	0.83	1.16	2.03	7.82	0.49	1.07	1.51	2.67	11.58
	Zone 2	0.28	0.46	0.65	1.11	3.29	0.41	0.82	1.17	1.97	8.37	0.52	1.12	1.59	2.69	12.78
	Zone 3	0.26	0.42	0.58	0.99	3.04	0.41	0.81	1.14	1.93	8.52	0.53	1.15	1.64	2.76	13.38
	Zone 4	0.40	0.64	0.91	1.55	5.32	0.53	0.95	1.35	2.31	9.55	0.64	1.21	1.70	2.95	12.88

Table 7
Percentage decrease by using adaptive patterns of the values of January of the FPR distributions in comparison with those obtained with static operational patterns.

Scenario	Zone	Percentage decrease (%)														
		Category I					Category II					Category III				
		Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max
RCP 2.6	Zone 1	−0.07	−0.27	−0.46	−0.79	−7.67	0.09	0.26	0.41	0.67	2.61	0.20	0.72	1.17	1.78	12.26
	Zone 2	−0.08	−0.18	−0.36	−0.59	−4.00	0.16	0.35	0.70	1.15	6.63	0.36	0.84	1.64	2.83	16.64
	Zone 3	−0.00	−0.04	−0.09	−0.17	−3.06	0.18	0.46	0.81	1.48	6.83	0.32	0.94	1.64	2.93	16.47
	Zone 4	−0.05	−0.23	−0.40	−0.62	−6.88	0.06	0.23	0.38	0.55	2.52	0.11	0.61	0.93	1.44	11.22
RCP 4.5	Zone 1	−0.07	−0.31	−0.54	−0.85	−8.56	0.07	0.20	0.31	0.47	1.51	0.17	0.62	0.96	1.43	10.66
	Zone 2	−0.04	−0.12	−0.22	−0.41	−3.37	0.17	0.37	0.73	1.27	6.68	0.36	0.87	1.65	2.93	16.54
	Zone 3	−0.01	−0.07	−0.14	−0.28	−3.67	0.17	0.43	0.75	1.32	6.05	0.31	0.91	1.55	2.70	15.47
	Zone 4	−0.03	−0.25	−0.40	−0.61	−7.84	0.05	0.16	0.23	0.37	1.22	0.10	0.46	0.71	1.31	9.29
RCP 8.5	Zone 1	−0.05	−0.27	−0.46	−0.73	−8.73	0.06	0.17	0.25	0.41	0.85	0.13	0.52	0.81	1.36	9.32
	Zone 2	−0.03	−0.10	−0.19	−0.35	−3.46	0.16	0.39	0.73	1.27	6.46	0.32	0.87	1.58	2.78	16.10
	Zone 3	0.00	−0.06	−0.11	−0.20	−3.83	0.13	0.40	0.67	1.12	5.66	0.22	0.80	1.32	2.20	14.65
	Zone 4	−0.02	−0.18	−0.32	−0.59	−7.77	0.03	0.12	0.18	0.30	0.56	0.05	0.31	0.48	0.91	7.33

Table 8
Percentage decrease by using adaptive patterns of the values of August of the FPR distributions in comparison with those obtained with static operational patterns.

Scenario	Zone	Percentage decrease (%)														
		Category I					Category II					Category III				
		Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max	Min	Q1	Q2	Q3	Max
RCP 2.6	Zone 1	0.72	1.25	1.77	2.99	12.50	0.90	1.64	2.32	3.90	15.52	1.02	1.99	2.79	4.67	18.27
	Zone 2	0.62	1.05	1.48	2.57	11.04	0.85	1.49	2.10	3.61	15.52	1.05	1.88	2.67	4.54	19.32
	Zone 3	0.63	1.05	1.47	2.56	10.72	0.85	1.46	2.06	3.55	15.01	1.05	1.86	2.64	4.51	19.16
	Zone 4	0.66	1.10	1.56	2.69	11.60	0.89	1.54	2.18	3.76	16.15	1.12	1.97	2.79	4.79	20.59
RCP 4.5	Zone 1	0.74	1.32	1.87	3.17	13.59	0.97	1.73	2.45	4.14	17.01	1.13	2.11	2.98	5.00	19.96
	Zone 2	0.64	1.09	1.53	2.67	11.52	0.86	1.51	2.13	3.67	15.88	1.07	1.92	2.71	4.64	20.03
	Zone 3	0.64	1.05	1.47	2.57	10.83	0.86	1.46	2.07	3.57	15.22	1.07	1.88	2.65	4.56	19.48
	Zone 4	0.68	1.13	1.60	2.75	11.98	0.91	1.57	2.22	3.82	16.59	1.15	2.01	2.84	4.88	21.12
RCP 8.5	Zone 1	0.79	1.40	1.98	3.38	14.69	1.02	1.83	2.59	4.40	18.56	1.20	2.23	3.15	5.32	21.87
	Zone 2	0.65	1.09	1.53	2.64	11.72	0.87	1.52	2.14	3.67	16.20	1.10	1.93	2.73	4.68	20.47
	Zone 3	0.65	1.07	1.51	2.61	11.24	0.87	1.50	2.11	3.64	15.74	1.10	1.92	2.71	4.65	20.12
	Zone 4	0.70	1.16	1.65	2.80	12.18	0.94	1.62	2.29	3.89	16.97	1.17	2.06	2.91	4.97	21.64

operational pattern was used as a reference to compare the variations obtained in the fuel poverty with the adaptive models. The thermal comfort model defined in the Spanish Building Technical Code was used as a static model, and the various categories from EN 16798-1:2019 were independently analysed for the adaptive model (Table 3). It is worth stressing that this research was conducted under the assumption that all users try to guarantee the maintenance of thermal comfort conditions in their dwellings. Thus, this research does not consider the fuel poverty cases that can be included with the M/2 indicator, i.e., when users do not use or slightly use HVAC systems, thus reducing the energy cost but affecting both their thermal comfort and health.

2.4. Fuel poverty assessment

Fuel poverty was analysed with the high share of energy expenditure in income (2 M) indicator used by the EPOV. This indicator is adjusted to the requirements as it could be applied to users who try to keep thermal comfort conditions in their dwellings. Thus, 2 M considers that the family units are in fuel poverty when the percentage relationship between the energy cost (*EC*) and the household income (*HI*) are greater than the national average. This study defined the percentage relationship as fuel poverty ratio (FPR) and is shown in Eq. (8). Regarding the value of the national median expenditure, a recent study by Sánchez-Guevara Sánchez et al. (2020) determined that the threshold

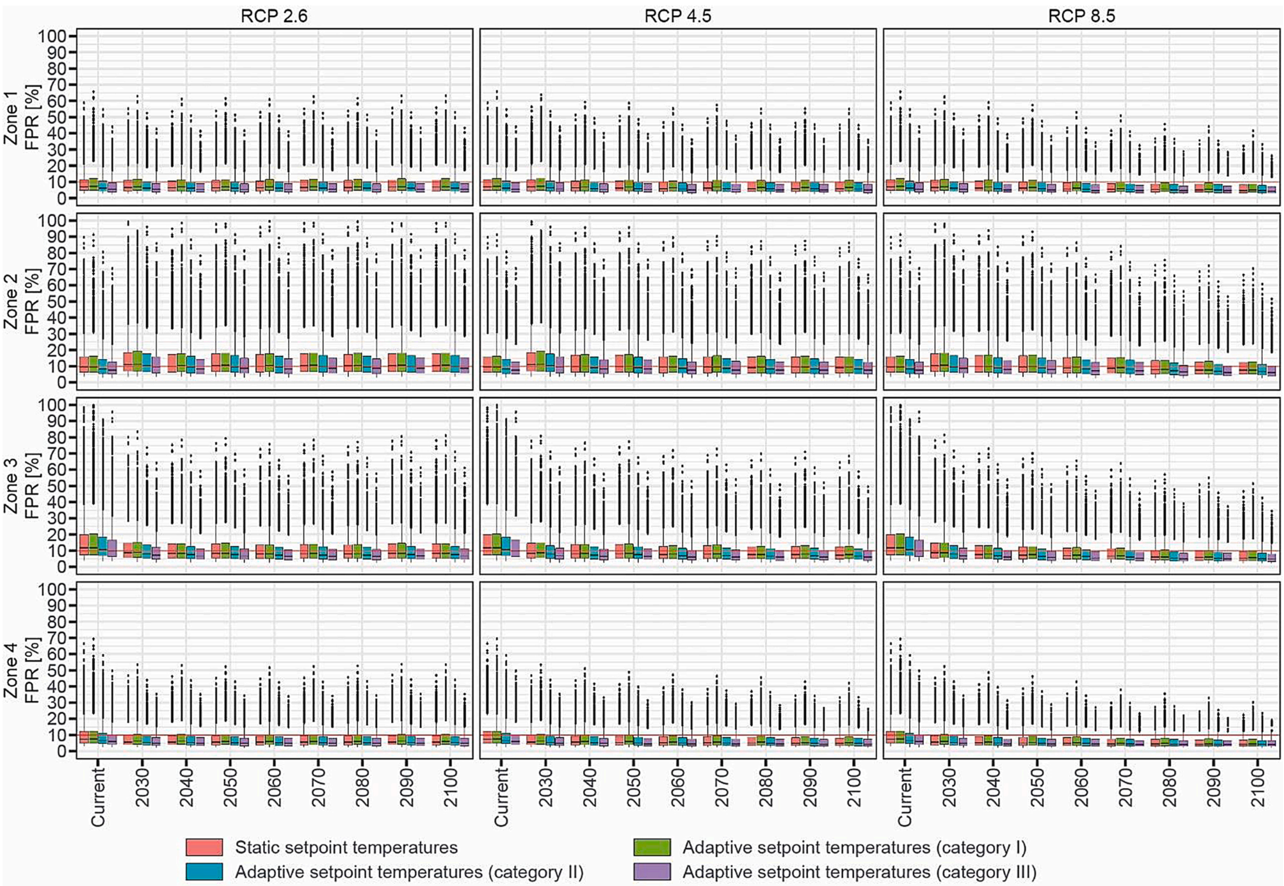

Fig. 12. Distribution of the annual FPR values in the most unfavourable winter month from 2030 to 2100 according to the type of operational pattern.

value for this indicator in Spain is 10 %, coinciding with the value established by Boardman (1991). Thus, this threshold value was used in this study: the cases obtaining a FPR greater than 10 % were in fuel poverty (Eq. (9)). Although this threshold value could vary over time, this study did not consider its variation to establish representative comparisons between the current scenario and climate change scenarios. It is worth stressing that the analysis was performed both at an annual and monthly scale because certain fuel poverty cases could be not detected at a monthly scale in a region if only annual data are used (Bienvenido-Huertas et al., 2021).

$$FPR = \frac{EC}{HI} \cdot 100 \left[\%\right] \tag{8}$$

$$\textit{Family unit in fuel poverty} \text{ if } FPR \geq 2M \ (10\%) \tag{9}$$

Thus, the following step was the determination process of both the energy cost and the household income. The energy cost was obtained by applying the legislation of the lighting rate existing in Spain to the energy consumption obtained from the simulation process with the various case studies. The rate used is the voluntary price for the small consumer (PVPC in Spanish), created and regulated by the Spanish Government in 2014 and whose aim is providing certain conditions of the lighting price that reduce consumers' risk (The Government of Spain, 2014). The energy cost that a family unit should pay is determined by summing the following concepts (Eq. (10)): energy term, power term, electricity tax, rent of measurement equipment, and value added tax. The energy term is the concept directly related to energy consumption as it is obtained by applying the cost of the kWh to the housing energy consumption (Eq. (11)). The cost value of the kWh varies according to the day and hour. The power term is a price paid to always guarantee power in the dwelling. The value of this term is obtained by applying costs of both grid access and marketing margin to the contracted power and to the number of days of the invoicing period (usually 30 or 31 days in a monthly invoicing period) (Eq. (12)). This study considered a contracted power of 4.6 kW. Finally, the costs of renting taxes and value added tax are percentage values applied to various concepts of the energy bill. The electricity tax increases by 5.1127 % the sum of the amounts of the energy and power term (Eq. (13)), whereas the value added tax increases by 21 % the sum of the cost of the energy term, power term, electricity tax and the rent of meters (Eq. (14)).

$$EC = ET + PT + ElT + CME + VAT \tag{10}$$

$$ET = \textit{Energy consumption} \cdot ETP \tag{11}$$

$$PT = 0.115188 \cdot P \cdot ND \tag{12}$$

$$ElT = 0.051127 \cdot (ET + PT) \tag{13}$$

$$VAT = 0.21 \cdot (ET + PT + ElT + CME) \tag{14}$$

Where *ET* is the energy term [€], *PT* s the power term [€], *ElT* is the amount of the electricity tax [€], *CME* is the renting cost of the measurement equipment [€], *VAT* is the value added tax [€], *ETP* is the energy term price [kWh/€], *ND* is the number of days of the invoicing period, and *P* is the contracted power [kW].

To determine the energy cost, the variation of the energy term and how it was addressed in the research should be stressed. In the years corresponding to the current scenario (2015, 2016 and 2017), actual data of the energy term were used. However, in the future years, an average value was determined for the energy term in comparison with the data recorded since the creation of the PVPC. This value was 0.11751 €/kWh. Other concepts, such as the electricity tax, did not vary in the

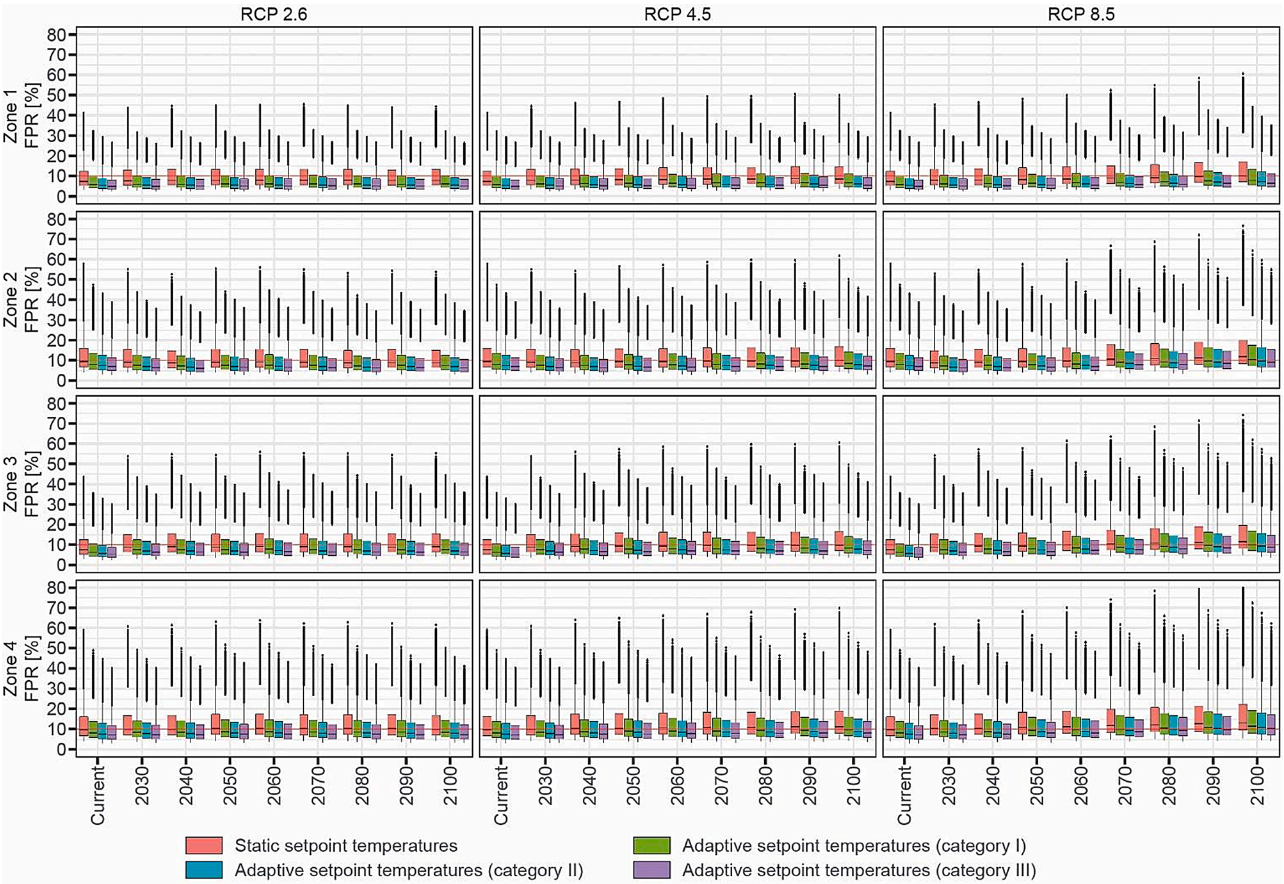

Fig. 13. Distribution of the annual FPR values in the most unfavourable summer month from 2030 to 2100 according to the type of operational pattern.

future scenarios.

On the other hand, 13 types of family unit's income levels were considered. To determine these levels, the public income indicator of multiple effects (IPREM in Spanish) was used. This indicator is used by governments for the family units that could benefit from social aids. Moreover, this indicator is used for accessing to social housing. The value associated today to the IPREM, with the proportional part of salary bonuses, is 626.63 €/month. This means that a family unit with incomes coinciding with the value of the IPREM receives 626.63 €/month. A total of 13 weighting factors were applied to this basis value to determine family units' incomes. The weighting factors were from 0.5 to 3.5 (Table 4).

2.5. Limitations of the study

It is worth stressing that in this kind of study there are several limitations with respect to the methodology established. First, fuel poverty assessment is based on the 2 M indicator, considering that users try to keep always certain thermal comfort conditions in their dwellings. The use of this criterion does not consider other possible fuel poverty phenomena, such as the family units with very low energy expenditure because thermal comfort conditions are reduced. In these cases, the casuistry is more complex, so social aspects should be considered in detail as these aspects could imply that users significantly reduce their energy consumption, thus affecting their health. Second, the analysis performed with the RCP scenarios throughout the 21st century has implied that some aspects related to the assessment of the 2 M indicator have been considered fixed. Thus, the values of the rates of the energy invoice and family units' incomes have been considered fixed. These values are expected to vary throughout the 21st century, but considering fixed values is interesting because the evolution of fuel poverty because of climate change can be representatively compared.

3. Results and discussion

3.1. Fuel poverty risk in the current scenario

First, the fuel poverty risk obtained in the current scenario (i.e., 2015, 2016 and 2017) was analysed. Fig. 4 shows the distribution of the annual FPR values with the various operational patterns considered. These distributions include all the combinations of cases and family unit's incomes described in Section 2. FPR values were first analysed with a static operational pattern (i.e., with static setpoint temperatures), and the values obtained at an annual scale varied according to the year and zone. Zone 1 obtained the lowest values in the quartile distributions, and zones 2 and 3 obtained the greatest values. In comparison with the values of zone 1, the other zones obtained an average increase between 0.63 and 0.99 % in the first quartile (Q1), between 0.89 and 1.55 % in the second quartile, and between 1.52 and 2.55 % in the third quartile (Q3). Zone 4 obtained lower values in the distribution quartiles in comparison with those obtained in zones 2 and 3. These differences arose from the impact of fuel poverty on the winter months, which was greater in zones 2 and 3. There were fuel poverty cases at an annual scale in all the zones analysed; however, the annual assessment did not show the variation throughout the year, so there could be more fuel poverty cases if the analysis is performed at a lower scale. Fig. 5 shows the distributions of the FPR values at a monthly scale of the current scenario in the four zones. The same tendency of the FPR values was detected in all zones, with the winter months (January and December) being the most unfavourable, and the summer months (July and August) obtaining the greatest values. Likewise, there were cases with FPR values greater than 10 % in all months; this percentage usually corresponded to the

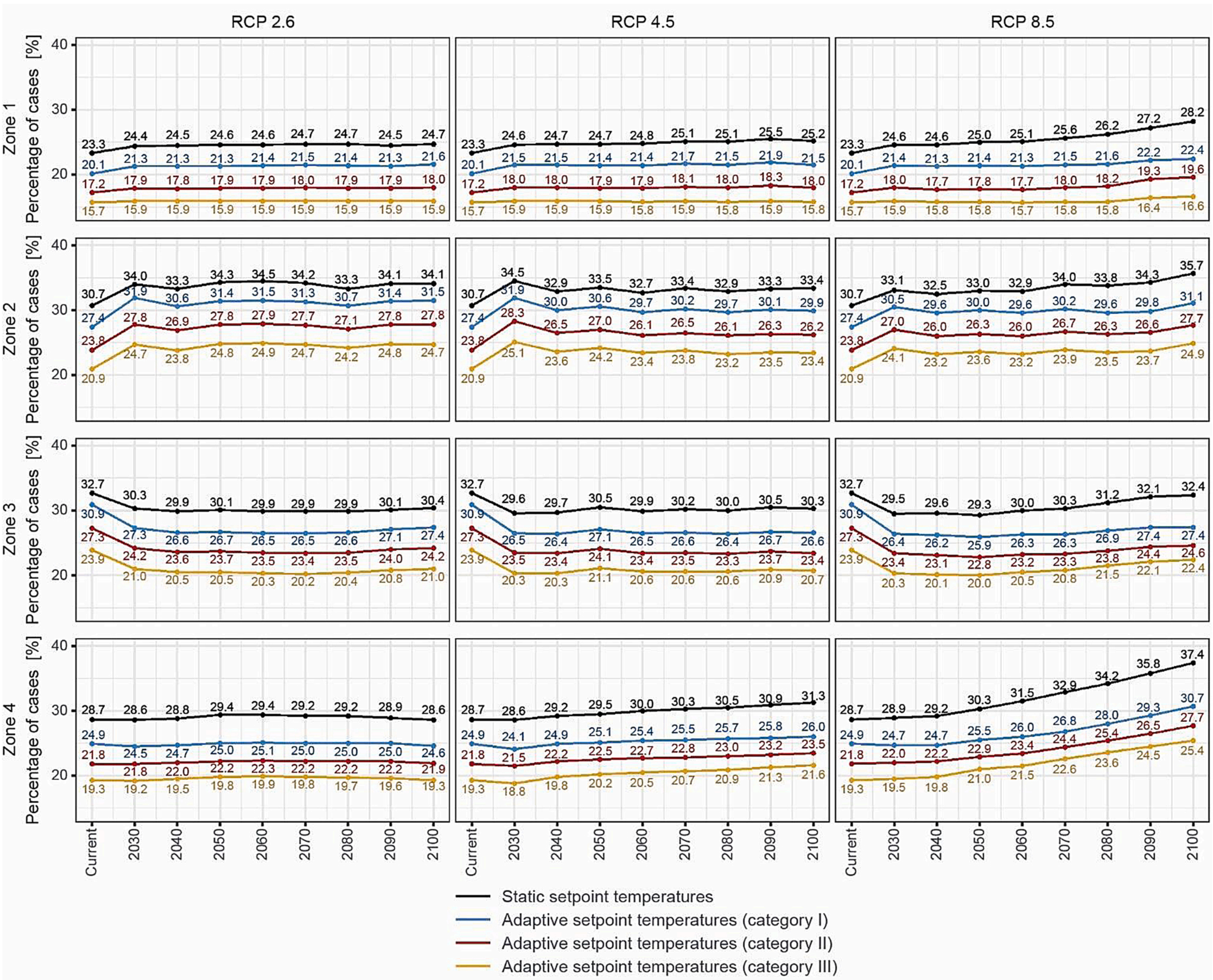

Fig. 14. Variation of the percentage of fuel poverty cases in the scenarios considered. The values of the current scenario were obtained through the average of the results of 2015, 2016, and 2017.

percentile of 75 % of the data distribution. The difference of the FPR values detected at an annual level arose from the relationship between the climate severity in the most unfavourable months and the high FPR values. Thus, zones 2 and 3 are characterised by obtaining high FPR values in the cold months: Q1 obtained values between 4.72 and 8.50 %, Q2 obtained values between 7.05 and 13.94 %, Q3 obtained values between 11.86 and 23.83 %, and the maximum values oscillated between 62.95 % and 141.145 %. Zones 2 and 3 also obtained high FPR values in the summer months because of the climate severity in the hot months. However, zone 4 obtained the greatest FPR values in the summer months. In this zone, the values of Q1, Q2 and Q3 of the distributions oscillated between 6.66 and 7.80 %, between 8.60 and 11 %, and between 14.81 and 18.54 %, respectively. This zone also obtained high FPR values in the cold months, although the summer months were more affected by fuel poverty. Finally, zone 1 showed the same tendency of greater severity in the cold and hot months, although obtained lower FPR values (Q1 lower than 5.84 %, Q2 lower than 8.22 %, and Q3 lower than 13.79 %). Thus, the use of static patterns implied high FPR values for all the combinations of cases and incomes considered in this research. FPR values had a different impact according to the zone analysed, although greater values were detected in the most unfavourable summer and winter months. These results showed the need to perform fuel poverty analyses on a monthly scale. Given the variable nature of climate throughout the year, the assessment of fuel poverty on an annual scale can hide situations of fuel poverty that occur in certain months of the year. In addition, the high values obtained in the summer months showed the need to expand the definitions and indicators associated with fuel poverty. In this regard, while the inability to keep houses warm is considered by some bodies (e.g., EPOV), the inability to keep them cold is not considered.

The use of adaptive operational patterns would reduce the fuel poverty risk of the family units in the current scenario because of the tendency of reducing the FPR values both at the annual and monthly scale. Moreover, the FPR values were reduced according to the type of category used for adaptive setpoint temperatures. This aspect can be seen in the decrease of the values of the distributions obtained at an annual scale (Table 5): (i) Category I obtained decreases between 0.24 and 0.44 % in Q1, between 0.31 and 0.62 % in Q2, and between 0.54 and 1.04 % in Q3; (ii) Category II obtained decreases between 0.63 and 0.78 % in Q1, between 0.91 and 1.12 % in Q2, and between 1.48 and 1.89 % in Q3; and (iii) Category III obtained decreases between 0.90 and 1.11 % in Q1, between 1.44 and 1.60 % in Q2, and between 2.27 and 2.70 % in Q3. Thus, Category I obtained a lower decrease in the FPR values, and the others obtained greater decreases. However, the decrease values with the categories varied according to whether fuel poverty risk was being assessing with heating or cooling systems. Table 5 shows the percentage decrease obtained in the most unfavourable summer and winter months. The use of Category I was not appropriate to reduce fuel

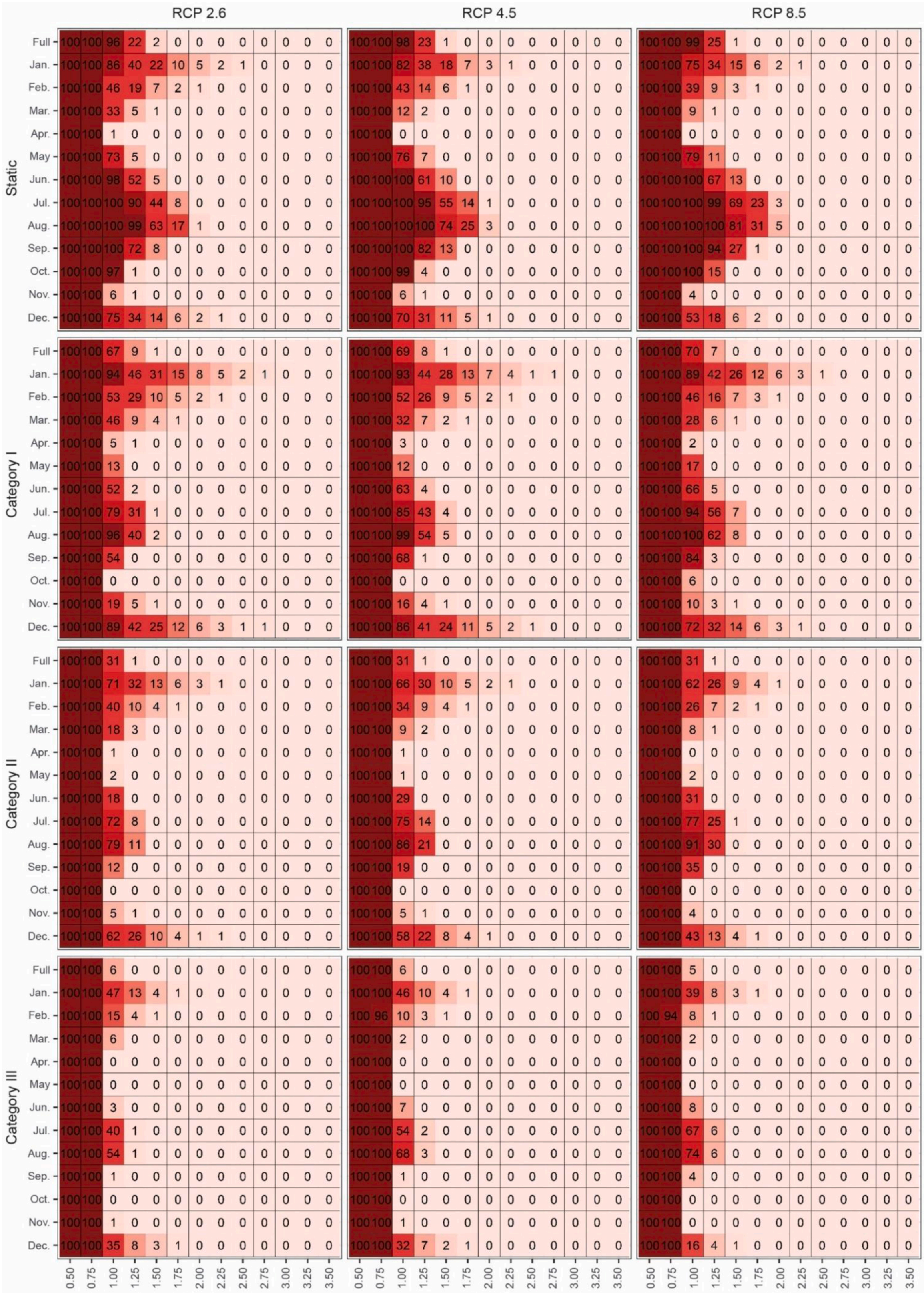

Fig. A1. Percentage of fuel poverty cases located in zone 1 in 2050.

poverty risk in winter. In this regard, the FPR values were not reduced in the winter months, increasing the FPR quartile distribution values with Category I. However, the other two categories did reduce the FPR values because the static setpoint temperature for heating recommended by the Spanish Building Technical Code is low, thus implying low energy consumption. The use of the lower limit of Category I generally obtains values greater than 17 or 20 °C, which are the values recommended for heating by the Spanish standard. Thus, the use of this category is limited

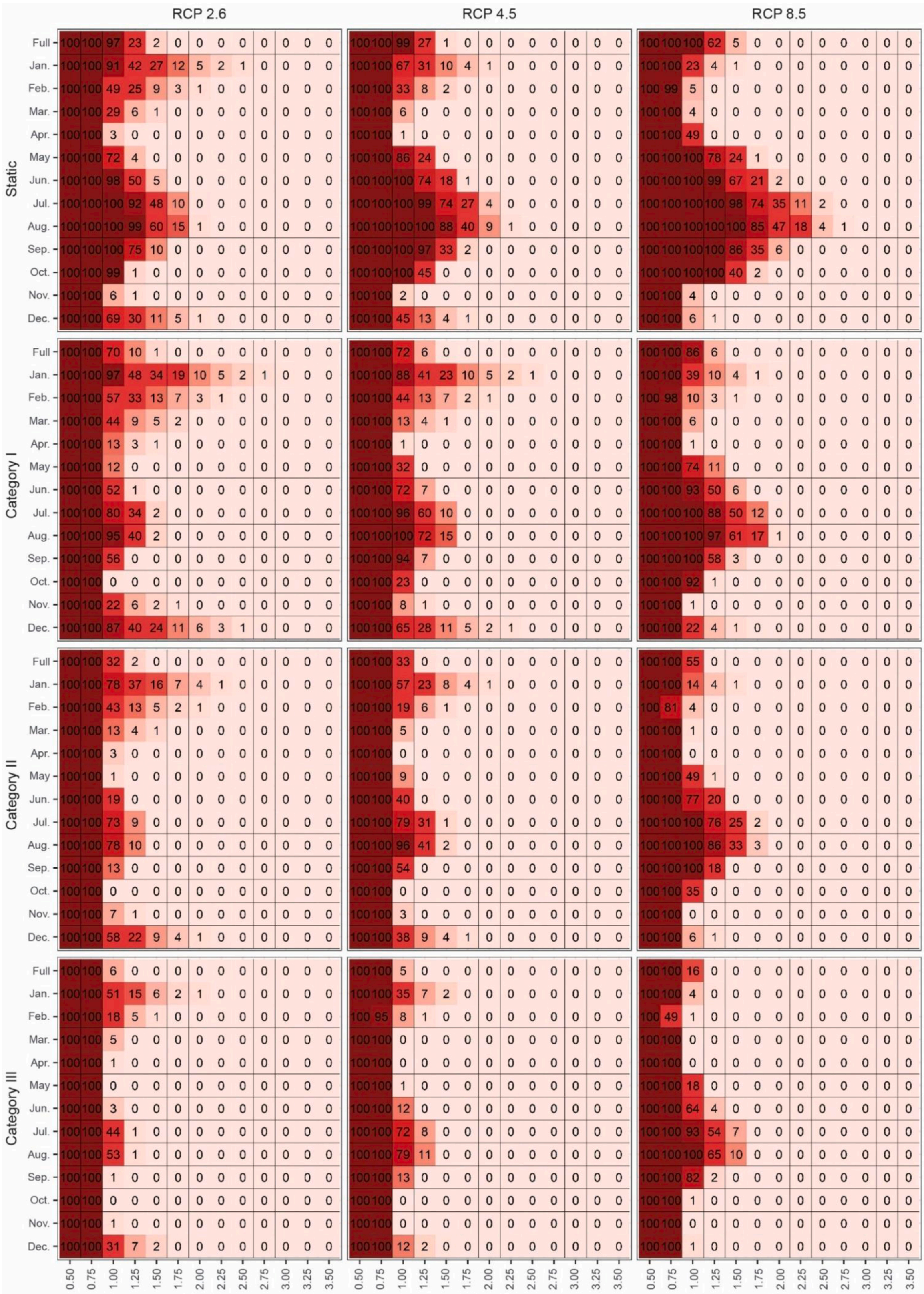

Fig. A2. Percentage of fuel poverty cases located in zone 1 in 2100.

to a certain extent. In this regard, it is worth stressing the many documents developed by Spanish bodies about the appropriate heating setpoint temperature. This would limit the potential of using adaptive setpoint temperatures in users with lower thermal adaptation, such as the elderly (Sánchez-Guevara Sánchez et al., 2019). In these cases, adaptive setpoint temperatures should be combined with other measures. Nonetheless, the use of the 3 categories of EN 16798-1:2019 decreased the annual values, particularly the maximum values which

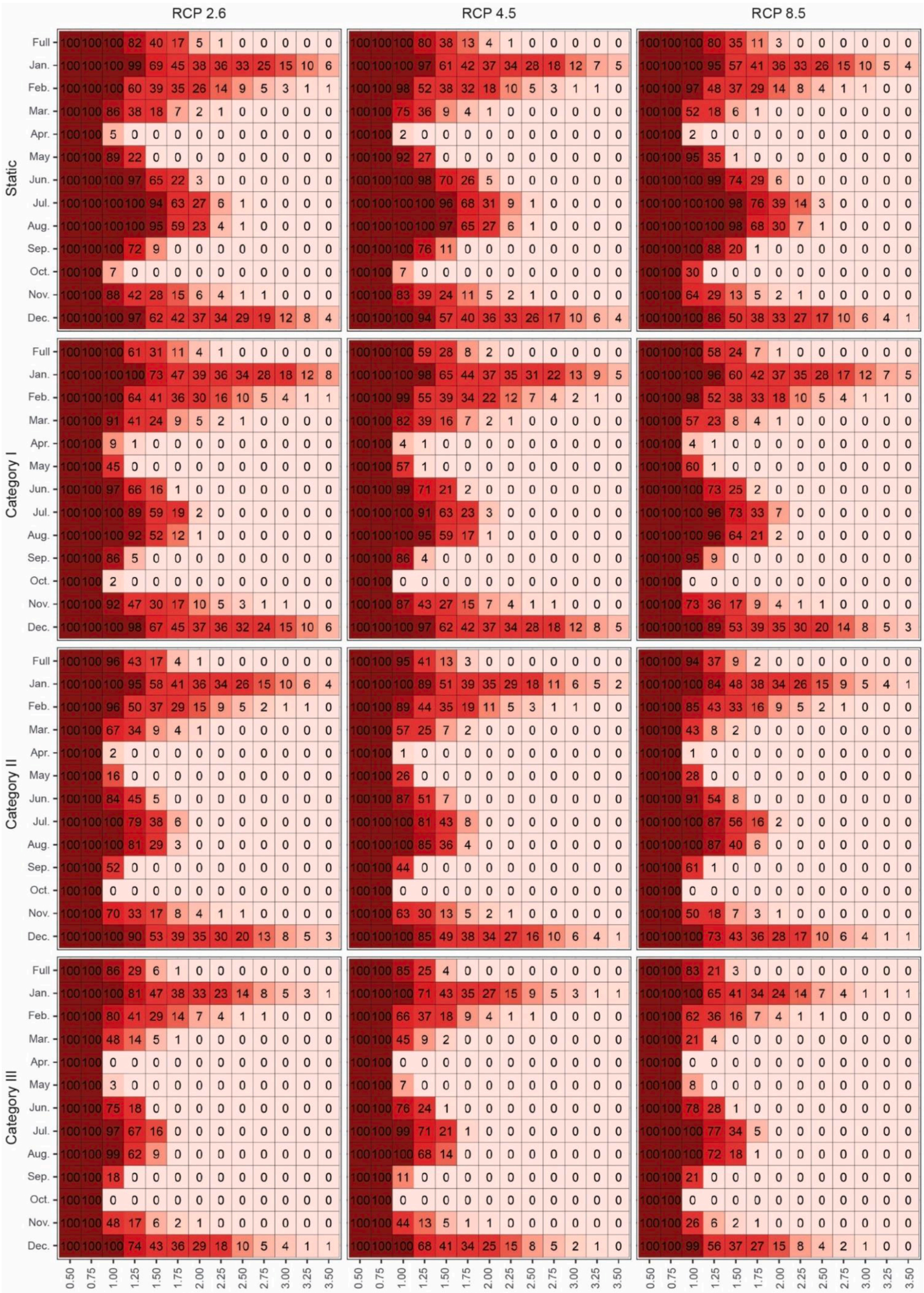

Fig. A3. Percentage of fuel poverty cases located in zone 2 in 2050.

were decreased between 7.82 and 18.54 %. This was due the effectiveness of the adaptive strategies to reduce fuel poverty risk in hot periods. Unlike the heating setpoint temperature, cooling static setpoint temperatures recommended by the Spanish Building Technical Code are not so effective. For this reason, the use of the adaptive patterns of the 3 categories of EN 16798-1:2019 reduced the FPR quartile distribution values, thus reducing the fuel poverty risk of family units in the summer months. This would meet the increasing needs for assessing fuel poverty

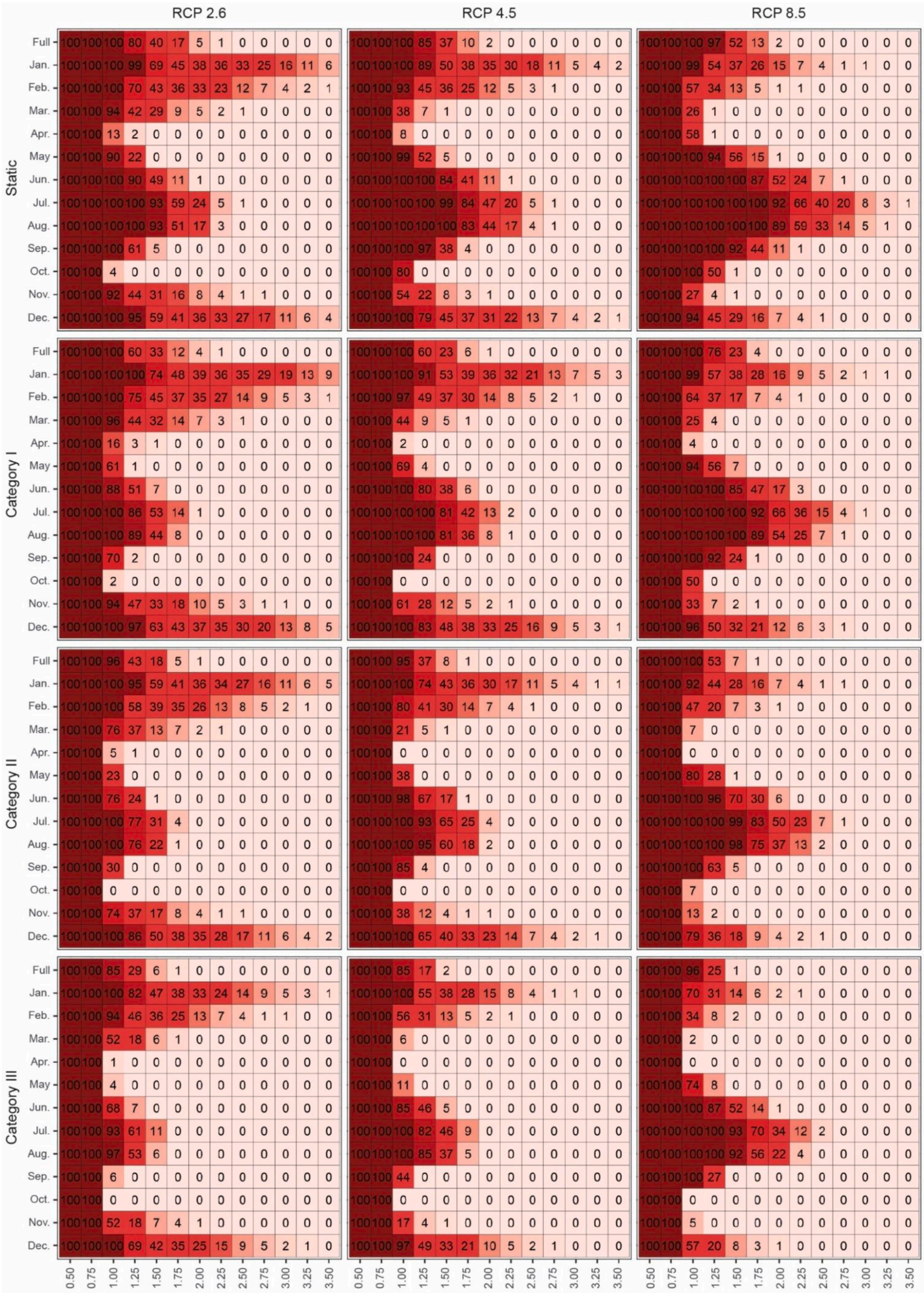

Fig. A4. Percentage of fuel poverty cases located in zone 2 in 2100.

in the hot months reported by Sánchez-Guevara Sánchez et al. (Sánchez-Guevara Sánchez et al., 2019), and could also contribute to the reduction of energy consumption in the building stock in the south of Europe, which makes the establishment of decarbonisation policies something of a challenge (Attia et al., 2017).

Thus, adaptive setpoint temperatures could reduce fuel poverty cases in the four zones in the current scenario in comparison with the cases using static patterns. However, as fuel poverty is a phenomenon

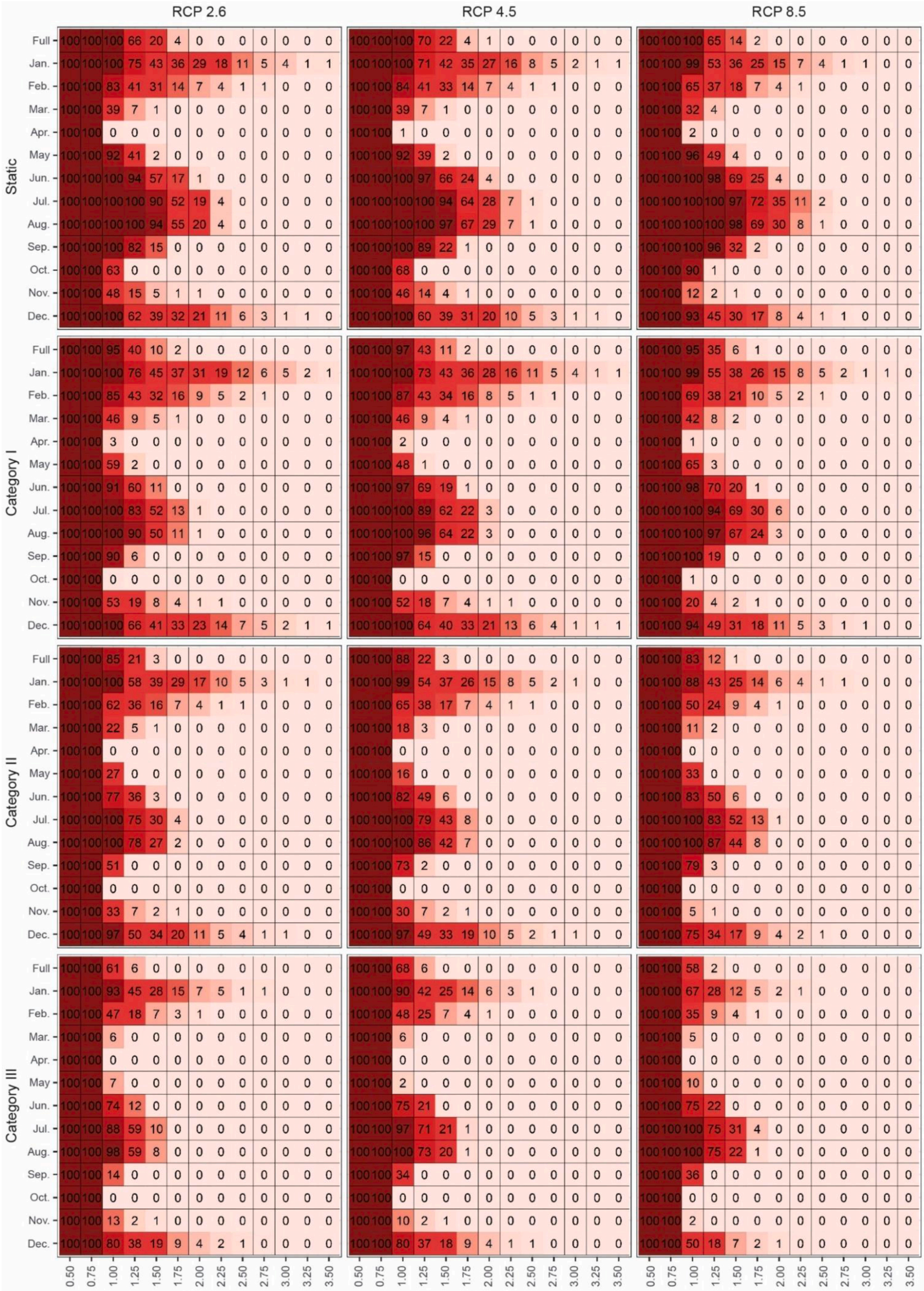

Fig. A5. Percentage of fuel poverty cases located in zone 3 in 2050.

including technical and social aspects, the effectiveness of the use of adaptive setpoint temperatures is limited according to the family units' incomes. To understand this aspect, the percentage of fuel poverty cases was assessed. Figs. 6–9 show the heatmaps of the percentages of fuel poverty cases obtained in zones 1, 2, 3 and 4. Family units with incomes lower than the value of the IPREM did not reduce the fuel poverty risk by using adaptive setpoint temperatures. In these cases, their income levels were so low that the FPR value was always greater than 10 %. To avoid

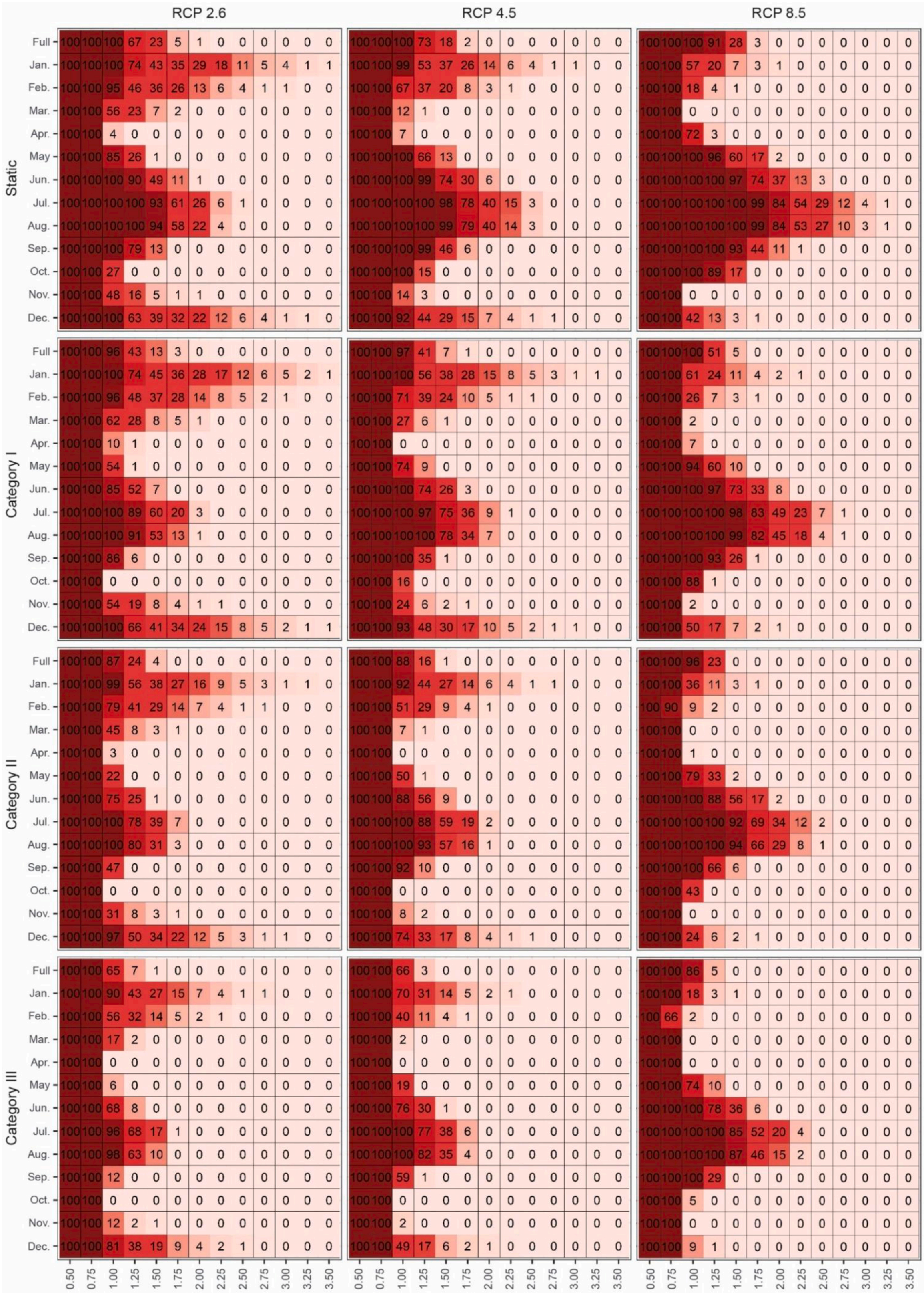

Fig. A6. Percentage of fuel poverty cases located in zone 3 in 2100.

fuel poverty risk, adaptive operational patterns should be combined with social aids that partially or totally reduce the energy expense of these family units. The family units with income values coinciding with the IPREM could also be under high fuel poverty risk in the most unfavourable months. The use of static patterns obtained values of 100 % in these months. However, the use of adaptive setpoint temperatures reduced in some zones (e.g., zone 1) the percentage of fuel poverty cases for this income level. To detect a greater effectiveness level of the

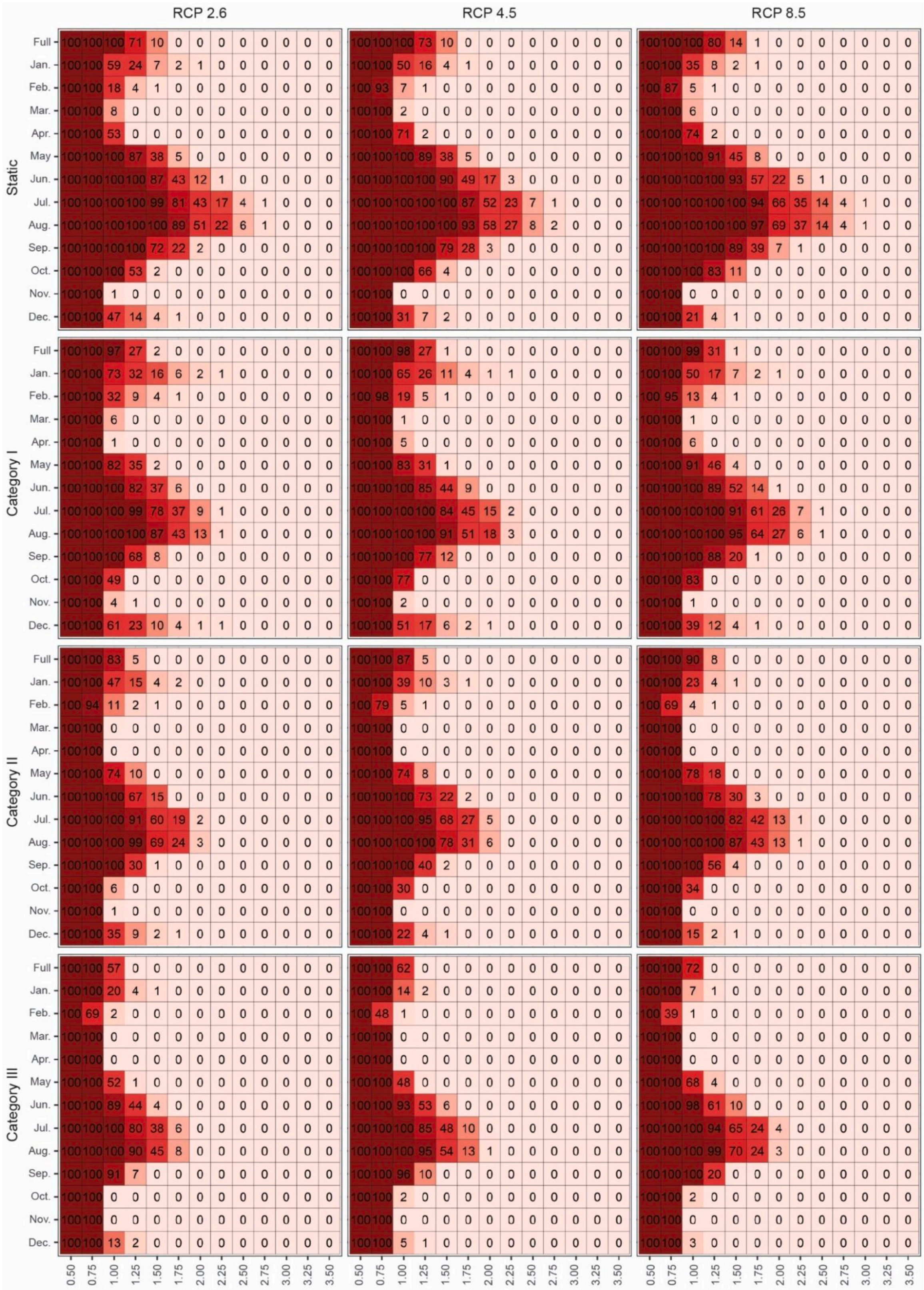

Fig. A7. Percentage of fuel poverty cases located in zone 4 in 2050.

adaptive strategies to reduce significantly or to remove the fuel poverty risk, family units' income should be greater than the value of the IPREM. Likewise, the heatmaps showed the impact of fuel poverty on the four zones: it was high in the winter months of zone 3, and in zone 1 the impact was very low in family units with incomes greater than twice the IPREM. The use of Categories II and III obtained the greatest decreases of fuel poverty cases, although family units were required to have an income level greater than the IPREM. This aspect could also be applied

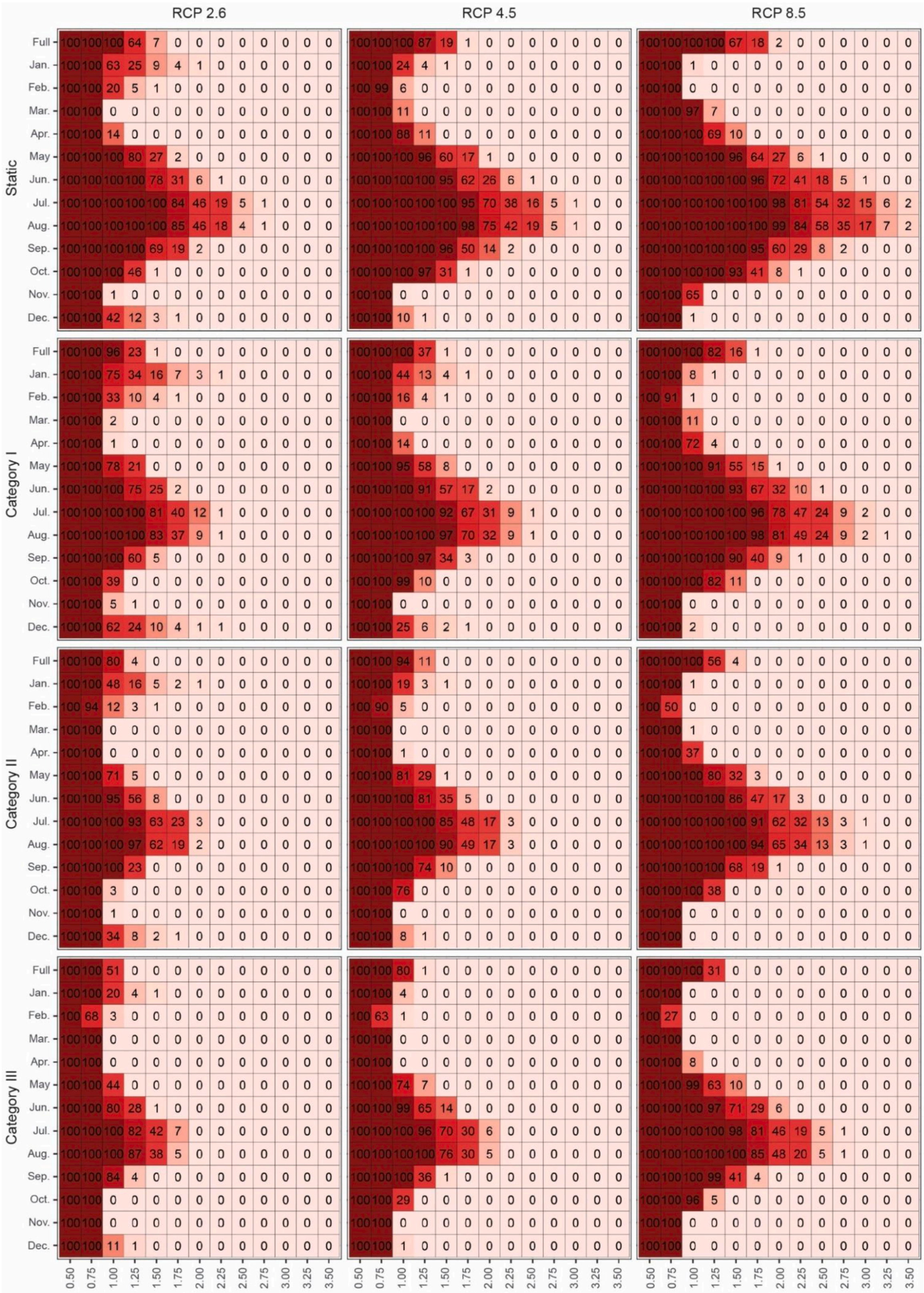

Fig. A8. Percentage of fuel poverty cases located in zone 4 in 2100.

together with other energy saving strategies, such as the façade improvement, although family units' investment cost should be considered in these cases. The use of adaptive operational patterns has the advantage that an economic investment is not required to be made by the family unit if an HVAC system is available, so the only required aspect would be training and informing users about the most appropriate operational patterns. In this regard, the energy saving policies established in the various countries have not exploited this option, except the setsuden campaign created by the Japanese government and consisting in that office buildings use a cooling setpoint temperature of 28 °C in summer (Indraganti, Ooka, & Rijal, 2013). However, the policy design for residential buildings is an aspect that should be exploited by governments to guarantee a lower impact of fuel poverty, particularly if the energy improvement of the building stock is so low as it is today (Ortiz & Salom, 2019).

3.2. Fuel poverty risk in the climate change scenario

Regarding the impact of climate change on fuel poverty risk, it is expected that climate variations change the tendencies of the distributions of FPR, although it depends on the RCP scenario. As with the current scenario, the results obtained were analysed at an annual scale (Fig. 10). In the case of the static operational pattern, climate change increased the FPR quartile distribution values. However, the effect was different in each zone and scenario: (i) in the period 2030–2100, zone 1 increased the quartile values between 0.05 and 0.11 % with RCP 2.6, between 0.09 and 0.17 % with RCP 4.5, and between 0.45 and 1.06 % with RCP 8.5, (ii) in zone 2, between 0.01 and 0.03 % with RCP 2.6, between 0.07 and 0.14 % with RCP 4.5, and between 0.31 and 0.69 % with RCP 8.5, (iii) in zone 3, between 0.01 and 0.02 % with RCP 2.6, between 0.09 and 0.15 % with RCP 4.5, and between 0.32 and 0.70 % with RCP 8.5, and (iv) in zone 4 there was no increase with RCP 2.6, whereas RCP 4.5 and RCP 8.5 obtained increases between 0.29 and 0.70 % and between 0.99 and 2.41 %, respectively. Thus, climate change affected the zones in different ways. In zones 2 and 3, with high annual FPR values, climate change had a lower effect, whereas in zone 4 (characterised by a high climate severity in summer in the current scenario), the FPR distribution values highly increased with RCP 4.5 and RCP 8.5. The reason was the effect of climate change on the FPR distribution value in all months of the year. Fig. 11 shows the monthly FPR distribution values in 2050 and 2100 in each zone using static operational patterns. In zones 2 and 3, in which fuel poverty was very high in the winter months, it changed in the climate change scenario. Thus, the greatest severity in the summer months would imply that the FPR quartile distribution values are greater in the summer months. In this regard, the average FPR quartile distribution values in the summer months were greater than in the winter months between 0.73 % (RCP 2.6 in 2050) and 6.94 % (RCP 8.5 in 2100). This variation generated that lower effect of climate change on the annual FPR values by reducing the fuel poverty risk in the cold months. Nevertheless, the percentage of cases considered in this study under fuel poverty risk in the winter months was still high. This can be seen in the values of the third quartile of the data distribution, obtaining values greater than 10 %. Only zone 4 was characterised by obtaining FPR distribution values lower than 10 % in the winter months. Regarding the summer months, the use of both climate change and static operational patterns increased the FPR values in all cases: (i) in zones 2 and 3, the quartile values oscillated between 6.35 and 8.26 %, between 8.95 and 11.65 %, and between 15.08 and 19.66 % in Q1, Q2 and Q3, respectively. Likewise, the maximum values were high, oscillating between 55 and 79.04 % in zone 2 and between 53.61 and 74.40 % in zone 3; (ii) zone 4 obtained the greatest values in summer, with values oscillating between 7.05 and 9.21 % in Q1, between 9.94 and 12.99 % in Q2, between 16.76 and 21.91 % in Q3, and between 60.58 and 83.61 % in the maximum values; and (iii) zone 1 obtained the lowest values of FPR in summer, with values between 5.28 and 6.84 % in Q1, between 7.43 and 9.64 in Q2, between 12.49 and 16.24 % in Q3, and between 41.55 and 57.82 % in the maximum values. Thus, the FPR distributions values were greater in the summer months in the RCP scenarios in comparison with the months of the current scenario. This aspect shows the limitations of the usage pattern based on static setpoint temperatures. The common pattern of closing the windows and using an inefficient cooling setpoint temperature would put families in more extreme situations and would contribute to more cases of fuel poverty. The climatic trends of the RCP scenarios show the need for a more sustainable use of HVAC systems that would provide greater financial relief to families.

If users used adaptive operational patterns, FPR values would be reduced. Table 6 shows the saving obtained in the annual FPR values in comparison with the static operational patterns, and Fig. 10 shows the box plots of the FPR value distributions. The decrease obtained at an annual scale was very similar among the climate change scenarios. The percentage decrease values presented a standard deviation oscillating between 0.05 and 0.23 per quartile and category. However, the FPR values significantly varied at a monthly scale. Tables 7 and 8 show the decrease percentages obtained with the adaptive strategies in the most unfavourable winter and summer months, and Figs. 12 and 13 show the FPR distribution values. The adaptive strategies still had the same tendencies as in the current scenario. Thus, Category I was not a valid option to reduce fuel poverty cases in winter; however, the other categories reduced these cases. Likewise, all categories were valid in summer to reduce fuel poverty cases. Although these tendencies were the same, the effectiveness of the adaptive strategies to reduce fuel poverty cases varied in comparison with the current scenario: (i) the FPR percentage decrease values in winter were lower than those obtained in the current scenario between 0.03 and 9.57 % (i.e., the FPR value was less reduced in the winter months of the RCP); and (ii) the FPR percentage decrease values in summer increased from 0.02 to 21.87% (i.e., the FPR values were more reduced in the summer months of the RCP). Thus, the results showed the great effectiveness of the adaptive operational patterns to reduce the fuel poverty risk in the months in which air conditioning systems are used throughout the 21st century. This becomes important if a greater demand to use these systems throughout the year is considered. In some scenario-zone combinations (e.g., zone 4 in RCP 8.5), the use of air conditioning systems was required from March to November. This means that the effectiveness of adaptive setpoint temperatures could encompass the main use of HVAC systems in the future. Nonetheless, the limitations associated with Category I suggest using only the upper limit. If either Category II or III is used, the lower limit could be used to configure heating setpoint temperatures.

Thus, the percentage decrease obtained with adaptive strategies was the same at an annual scale, but the percentage deviations varied in summer and winter. Consequently, the number of fuel poverty cases was the same in the various scenarios as the percentage decrease values were referenced to the FPR values of the static operational pattern. The number of fuel poverty cases should therefore be analysed. Fig. 14 shows the annual average values of the percentage of fuel poverty cases in the RCP scenarios. Figs. A1–A8 include the heatmaps with the analysis per month and per income levels considered in this study. It was detected, by analysing the annual values, that the percentage of fuel poverty cases presented a horizontal tendency in RCP 2.6. These results were consistent with the characteristics of that scenario, as the policies focused on reducing climate change effects were successful. However, fuel poverty cases increased in RCP 4.5 and RCP 8.5, with an especial impact on the latter. This scenario could significantly increase fuel poverty cases, particularly in those presenting greater climate severity in the summer months in the current scenario. Thus, zone 4 presented an increase in fuel poverty cases of 8.4 % with the static operational patterns. However, the increase trend was continuous in all climatic zones with RCP 4.5 and RCP 8.5. Thus, a steady increase in fuel poverty cases was detected, including Zone 1 with a low percentage of fuel poverty. This increase was obtained with all operational patterns. Nevertheless, the use of adaptive operational patterns significantly reduced fuel poverty cases with the best use of HVAC systems. Nonetheless, the strategy of reducing building energy consumption did not prevent family units with low income levels from fuel poverty. In this regard, the threshold of the minimum income level required to guarantee the effectiveness of adaptive strategies was increased in comparison with the current scenario. Thus, in the summer months, family units with incomes lower than 1.50 times the IPREM could easily be in fuel poverty, and the use of adaptive strategies could not prevent them from this situation. This meant a great variation in comparison with the current scenario, in which family units with those difficulties were those with incomes lower than the IPREM. Thus, family units' income levels should be increased throughout the 21st century. This aspect, together with others such as unemployment and low wages, could contribute to more fuel poverty cases in the future. Thus, policies should be designed not only to improve the energy of buildings, but to improve the working conditions of families. This is a crucial aspect, particularly in warmer climatic zones where the effects of climate change are more significant in the fuel poverty threshold. It is worth stressing the great variability that the FPR value could present according to both the RCP scenario and the great risk implied by the evolution of carbon dioxide emissions with RCP 8.5. The climate conditions of RCP 8.5 at the end of the century could be a great challenge to prevent family units from being in fuel poverty in the hot months.

4. Conclusions

This research assesses the effectiveness of the adaptive strategies to reduce fuel poverty throughout the 21st century considering the RCP scenarios. The study, focused on Andalusia, is an approach to a geographic area with the four zones defined by applying the adaptive strategies. The parametric study of the representative social housing is composed of 6,528 case studies in which the climate change scenarios have been used, and the fuel poverty risk has been assessed at a monthly and annual scale.

The results for the current scenario show that the fuel poverty risk is reduced in the four zones at an annual scale if adaptive strategies are applied; the risk is lower in Category III because the tolerance ranges are greater. In the monthly study, zones 2 and 3 are characterised by obtaining high FPR values in the cold months, both with static patterns and Category I, slightly reducing FPR; however, zone 4 is characterised by obtaining the greatest values in the summer months. It is worth stressing the difficulty of reducing the fuel poverty risk in family units with incomes lower or similar to the value of the IPREM, with the use of adaptive setpoint temperatures being always effective if the family unit's incomes are greater than the value of the IPREM.

Fuel poverty risk, considering the impact of climate change, tends to increase in the case of the static operational pattern, although its influence is different according to both the RCP chosen and each zone (it is greater in zone 4. If users used adaptive operational patterns, FPR would be reduced at the annual scale. However, all categories are valid in the monthly analysis to reduce fuel poverty, except Category I in winter, with the reduction being very significant in the summer months. Results greatly vary according to the RCP chosen. RCP 2.6 does not significantly vary as it is in line with current energy policies; however, fuel poverty cases increase in RCP 4.5 and RCP 8.5, thus affecting the family units considerably exceeding the IPREM.

This research stresses that, although the global warming levels considered for the future (RCP 2.6) are kept, the fuel poverty situation will be aggravated by the static operational patterns, so the adaptive strategies are a viable option to reduce fuel poverty if family units' incomes are increased over the IPREM. Likewise, the results show that the income threshold to avoid situations of fuel poverty will be higher in the future. Therefore, the efficient use of HVAC systems through adaptive setpoint temperatures would guarantee a lower energy vulnerability in families. The configuration of the adaptive setpoint temperatures of this study is based on the adaptive model of EN 16798-1:2019 (i.e., the thermal comfort limits based on the fluctuation of the outdoor temperature). Therefore, this approach has been used for the adaptive thermal comfort limits in both the current and future scenarios. Although this approach allows the various scenarios to be compared, the adaptive model could vary throughout the 21st century. Definitions of the adaptive models could vary in the future, thus varying the decrease percentages detected in the study. Nonetheless, the potential of energy savings and the reduction of fuel poverty cases by using an adaptive setpoint temperature is expected to be similar due to the low efficiency of static setpoint temperatures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

References

Albertí, J., Raigosa, J., Raugei, M., Assiego, R., Ribas-Tur, J., Garrido-Soriano, N., et al. (2019). Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels. *Sustainable Cities and Society, 47*(February), Article 101467. https://doi.org/10.1016/j.scs.2019.101467

American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE). (2017). In ASHRAE Inc (Ed.), *ASHRAE Standard 55-2017 thermal environmental conditions for human occupancy*.

Aminipouri, M., Rayner, D., Lindberg, F., Thorsson, S., Knudby, A. J., Zickfeld, K., et al. (2019). Urban tree planting to maintain outdoor thermal comfort under climate change: The case of Vancouver's local climate zones. *Building and Environment, 158* (February), 226–236. https://doi.org/10.1016/j.buildenv.2019.05.022

Attia, S., Eleftheriou, P., Xeni, F., Morlot, R., Ménézo, C., Kostopoulos, V., et al. (2017). Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. *Energy and Buildings, 155*(2017), 439–458. https://doi.org/10.1016/j.enbuild.2017.09.043

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Opebiyi, A. A. (2018). Electrical energy poverty among micro-enterprises: Indices estimation approach for the city of Ibadan, Nigeria. *Sustainable Cities and Society, 37*(June 2017), 344–357. https://doi.org/10.1016/j.scs.2017.10.007

Bellia, L., Pedace, A., & Fragliasso, F. (2015). The role of weather data files in Climate-based Daylight Modeling. *Solar Energy, 112*, 169–182. https://doi.org/10.1016/j.solener.2014.11.033

Berardi, U., & Jafarpur, P. (2020). Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews, 121*(December 2019), Article 109681. https://doi.org/10.1016/j.rser.2019.109681

Bienvenido-Huertas, D., Sánchez-García, D., & Rubio-Bellido, C. (2021). Adaptive setpoint temperatures to reduce the risk of energy poverty? A local case study in Seville. *Energy and Buildings, xxxx*, Article 110571. https://doi.org/10.1016/j.enbuild.2020.110571

Bienvenido-Huertas, D., Rubio-Bellido, C., Farinha, F., Oliveira, M. J., & Pérez-Ordóñez, J. L. (2020). Evaluating the potential of adaptive comfort approach using historic data to reduce energy consumption in buildings in southern Spain. *Building and Environment, 185*(August). https://doi.org/10.1016/j.buildenv.2020.107313

Bienvenido-Huertas, D., Sánchez-García, D., Pérez-Fargallo, A., & Rubio-Bellido, C. (2020). Optimization of energy saving with adaptive setpoint temperatures by calculating the prevailing mean outdoor air temperature. *Building and Environment, 170*(July 2019). https://doi.org/10.1016/j.buildenv.2019.106612

Bienvenido-Huertas, D., Sánchez-García, D., & Rubio-Bellido, C. (2020). Analysing natural ventilation to reduce the cooling energy consumption and the fuel poverty of social dwellings in coastal zones. *Applied Energy, 279*, Article 115845. https://doi.org/10.1016/j.apenergy.2020.115845

Boardman, B. (1991). *Fuel poverty: From cold homes to affordable warmth*. John Wiley & Sons Ltd.

Bouzarovski, S., & Petrova, S. (2015). A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. *Energy Research & Social Science, 10*, 31–40. https://doi.org/10.1016/j.erss.2015.06.007

Bouzarovski, S., Petrova, S., & Tirado-Herrero, S. (2014). From fuel poverty to energy vulnerability: The importance of services, needs and practices. In University of Essex (Ed.), *SPRU working paper series SWPS 2014* (Vol. 25, pp. 1–28). https://doi.org/10.2139/ssrn.2743143

Carlucci, S., Bai, L., de Dear, R., & Yang, L. (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment, 137*, 73–89. https://doi.org/10.1016/j.buildenv.2018.03.053
Cellura, M., Guarino, F., Longo, S., & Tumminia, G. (2018). Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. *Energy for Sustainable Development, 45*(2018), 46–65. https://doi.org/10.1016/j.esd.2018.05.001
Chai, J., Huang, P., & Sun, Y. (2020). Differential evolution - based system design optimization for net zero energy buildings under climate change. *Sustainable Cities and Society, 55*(December 2019), Article 102037. https://doi.org/10.1016/j.scs.2020.102037
Ciancio, V., Salata, F., Falasca, S., Curci, G., Golasi, I., & de Wilde, P. (2020). Energy demands of buildings in the framework of climate change: An investigation across Europe. *Sustainable Cities and Society*. , Article 154244. https://doi.org/10.1016/j.scs.2020.102213
D'Agostino, D., Mele, L., Minichiello, F., & Renno, C. (2020). The use of ground source heat pump to achieve a net zero energy building. *Energies, 13*(13). https://doi.org/10.3390/en13133450
da Guarda, E. L. A., Domingos, R. M. A., Jorge, S. H. M., Durante, L. C., Sanches, J. C. M., Leão, M., et al. (2020). The influence of climate change on renewable energy systems designed to achieve zero energy buildings in the present: A case study in the Brazilian Savannah. *Sustainable Cities and Society, 52*(July 2019). https://doi.org/10.1016/j.scs.2019.101843
Dagoumas, A., & Kitsios, F. (2014). Assessing the impact of the economic crisis on energy poverty in Greece. *Sustainable Cities and Society, 13*, 267–278. https://doi.org/10.1016/j.scs.2014.02.004
de Dear, R., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: Revision to ASHRAE standards 55. *Journal of Energy and Buildings, 34*, 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1
de Dear, R., & Brager, G. S. (2001). The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology, 45*(2), 100–108.
de Haas, R., & van Horen, N. (2012). International shock transmission after the Lehman Brothers collapse: Evidence from syndicated lending. *American Economic Review, 102*(3), 231–237. https://doi.org/10.1257/aer.102.3.231
de Rubeis, T., Falasca, S., Curci, G., Paoletti, D., & Ambrosini, D. (2020). Sensitivity of heating performance of an energy self-sufficient building to climate zone, climate change and HVAC system solutions. *Sustainable Cities and Society, 61*(June), Article 102300. https://doi.org/10.1016/j.scs.2020.102300
Domínguez-Amarillo, S., Sendra, J. J., & Oteiza, I. (2016). *La envolvente térmica de la vivienda social. El caso de Sevilla, 1939 a 1979*. Madrid: Editorial CSIC.
European Commission. (2002). Directive 2002/91/EC of the European Parliament and of the council of 16 December 2002 on the energy performance of buildings. *Official Journal of the European Union*, 65–71. https://doi.org/10.1039/ap9842100196
European Commission. (2006). *Action plan for energy efficiency: Realising the potential*.
European Commission. (2014). In *Communication from the Commission, Europe 2020, 2014* pp. 1–5). https://doi.org/10.1007/s13398-014-0173-7.2, 1.
European Committee for Standardization. (2007). *EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor quality, thermal environment, lighting and acoustics*. European Committee for Standardization.
European Committee for Standardization. (2019). *EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acous*.
European Environment Agency. (2018). *Final energy consumption by sector and fuel (2016)*.
European Union. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union, 153*.
Fanger, P. O. (1970). In McGraw-Hill (Ed.), *Thermal comfort: Analysis and applications in environmental engineering*.
Feijó-Muñoz, J., Pardal, C., Echarri, V., Fernández-Agüera, J., Assiego de Larriva, R., Montesdeoca Calderín, M., et al. (2019). Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary islands. *Energy and Buildings, 188–189*, 226–238. https://doi.org/10.1016/j.enbuild.2019.02.023
Fernández-Agüera, J., Domínguez-Amarillo, S., Sendra, J. J., & Suárez, R. (2016). An approach to modelling envelope airtightness in multi-family social housing in Mediterranean Europe based on the situation in Spain. *Energy and Buildings, 128*, 236–253. https://doi.org/10.1016/j.enbuild.2016.06.074
Gangolells, M., Casals, M., Forcada, N., MacArulla, M., & Cuerva, E. (2016). Energy mapping of existing building stock in Spain. *Journal of Cleaner Production, 112*(June 2013), 3895–3904. https://doi.org/10.1016/j.jclepro.2015.05.105
Gercek, M., & Durmuş Arsan, Z. (2019). Energy and environmental performance based decision support process for early design stages of residential buildings under climate change. *Sustainable Cities and Society, 48*(February). https://doi.org/10.1016/j.scs.2019.101580
Ghose, A., McLaren, S. J., & Dowdell, D. (2020). Upgrading New Zealand's existing office buildings – An assessment of life cycle impacts and its influence on 2050 climate change mitigation target. *Sustainable Cities and Society, 57*(October 2019), Article 102134. https://doi.org/10.1016/j.scs.2020.102134
Gianfrate, V., Piccardo, C., Longo, D., & Giachetta, A. (2017). Rethinking social housing: Behavioural patterns and technological innovations. *Sustainable Cities and Society, 33*(October 2016), 102–112. https://doi.org/10.1016/j.scs.2017.05.015
Golmohamadi, H., Keypour, R., Bak-Jensen, B., & Radhakrishna Pillai, J. (2019). Optimization of household energy consumption towards day-ahead retail electricity price in home energy management systems. *Sustainable Cities and Society, 47*(February), Article 101468. https://doi.org/10.1016/j.scs.2019.101468
Gürdür Broo, D., Lamb, K., Ehwi, R. J., Pärn, E., Koronaki, A., Makri, C., et al. (2021). Built environment of Britain in 2040: Scenarios and strategies. *Sustainable Cities and Society, 65*. https://doi.org/10.1016/j.scs.2020.102645
Hatwaambo, S., Jain, P. C., Perers, B., & Karlsson, B. (2009). Projected beam irradiation at low latitudes using Meteonorm database. *Renewable Energy, 34*(5), 1394–1398. https://doi.org/10.1016/j.renene.2008.09.011
Healy, J. D. (2003). Excess winter mortality in Europe: A cross country analysis identifying key risk factors. *Journal of Epidemiology & Community Health, 57*(10), 784–789. https://doi.org/10.1136/jech.57.10.784, 2003.
Healy, J. D., & Clinch, J. P. (2002). Fuel poverty, thermal comfort and occupancy: Results of a national household-survey in Ireland. *Applied Energy, 73*(3–4), 329–343. https://doi.org/10.1016/S0306-2619(02)00115-0
Healy, J. D., & Clinch, J. P. (2004). Quantifying the severity of fuel poverty, its relationship with poor housing and reasons for non-investment in energy-saving measures in Ireland. *Energy Policy, 32*(2), 207–220, 2004.
Herrera, M., Natarajan, S., Coley, D. A., Kershaw, T., Ramallo-González, A. P., Eames, M., et al. (2017). A review of current and future weather data for building simulation. *Building Services Engineering Research and Technology*. https://doi.org/10.1177/0143624417705937. April, 014362441770593.
Indraganti, M., Ooka, R., & Rijal, H. B. (2013). Thermal comfort in offices in summer: Findings from a field study under the "setsuden" conditions in Tokyo, Japan. *Building and Environment, 61*, 114–132. https://doi.org/10.1016/j.buildenv.2012.12.008
Intergovernmental Panel on Climate Change. (2014). Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental Panel on climate change. In Intergovernmental Panel on Climate Change (Ed.), *Climate change 2013 - The physical science basis*. Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.004.
Invidiata, A., & Ghisi, E. (2016). Impact of climate change on heating and cooling energy demand in houses in Brazil. *Energy and Buildings, 130*(2016), 20–32. https://doi.org/10.1016/j.enbuild.2016.07.067
Jalaei, F., Guest, G., Gaur, A., & Zhang, J. (2020). Exploring the effects that a non-stationary climate and dynamic electricity grid mix has on whole building life cycle assessment: A multi-city comparison. *Sustainable Cities and Society, 61*(June). https://doi.org/10.1016/j.scs.2020.102294
Il Jeong, D., & Sushama, L. (2018). Projected changes to extreme wind and snow environmental loads for buildings and infrastructure across Canada. *Sustainable Cities and Society, 36*(December 2016), 225–236. https://doi.org/10.1016/j.scs.2017.10.004
Jiang, A., Liu, X., Czarnecki, E., & Zhang, C. (2019). Hourly weather data projection due to climate change for impact assessment on building and infrastructure. *Sustainable Cities and Society, 50*(June), Article 101688. https://doi.org/10.1016/j.scs.2019.101688
Kameni, M., Yvon, A., Kalameu, O., Asadi, S., Choudhary, R., & Reiter, S. (2019). Impact of climate change on demands for heating and cooling energy in hospitals: An in-depth case study of six islands located in the Indian Ocean region. *Sustainable Cities and Society, 44*(October 2018), 629–645. https://doi.org/10.1016/j.scs.2018.10.031
Karyono, K., Abdullah, B. M., Cotgrave, A. J., & Bras, A. (2020). The adaptive thermal comfort review from the 1920s, the present, and the future. *Developments in the Built Environment*. , Article 106192. https://doi.org/10.1016/j.dibe.2020.100032
Kikumoto, H., Ooka, R., Arima, Y., & Yamanaka, T. (2015). Study on the future weather data considering the global and local climate change for building energy simulation. *Sustainable Cities and Society, 14*(1), 404–413. https://doi.org/10.1016/j.scs.2014.08.007
Kurtz, F., Monzón, M., & López-Mesa, B. (2015). Energy and acoustics related obsolescence of social housing of Spain's post-war in less favoured urban areas. The case of Zaragoza. *Informes de La Construcción, 67*(Extra-1), m021. https://doi.org/10.3989/ic.14.062
Legendre, B., & Ricci, O. (2015). Measuring fuel poverty in France: Which households are the most fuel vulnerable? *Energy Economics, 49*, 620–628. https://doi.org/10.1016/j.eneco.2015.01.022
Liddell, C., & Guiney, C. (2015). Living in a cold and damp home: Frameworks for understanding impacts on mental well-being. *Public Health, 129*(3), 191–199.
Llorca, M., Rodriguez-Alvarez, A., & Jamasb, T. (2020). Objective vs. subjective fuel poverty and self-assessed health. *Energy Economics, 87*. https://doi.org/10.1016/j.eneco.2020.104736
Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., & de Dear, R. (2016). Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment, 98*, 55–70. https://doi.org/10.1016/J.BUILDENV.2015.12.019
Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., et al. (2018). Global warming of 1.5 C. *An IPCC Special Report on the Impacts of Global Warming of (Vol. 1)*.
McCartney, K. J., & Nicol, J. F. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings, 34*, 623–635.
METEONORM. (2019). *Handbook part II: Theory (version 7.3.1) (issue January)*.
(Ola) Michalec, A., Hayes, E., & Longhurst, J. (2019). Building smart cities, the just way. A critical review of "smart" and "just" initiatives in Bristol, UK. *Sustainable Cities and Society, 47*(March), Article 101510. https://doi.org/10.1016/j.scs.2019.101510
Middlemiss, L., & Gillard, R. (2015). Fuel poverty from the bottom-up: Characterising household energy vulnerability through the lived experience of the fuel poor. *Energy Research & Social Science, 6*, 146–154.

Montalbán Pozas, B. (2018). Energy assesment of housing in extremadura community. *Informes de La Construcción, 70*(551), 265. https://doi.org/10.3989/ic.16.152
Nakicenovic, N., & Swart, R. (2000). In Cambridge University Press (Ed.), *Special report on emissions scenarios. A special report of working group III of the intergovernmental panel on climate change*.
Ortiz, J., & Salom, J. (2019). Health and related economic effects of residential energy retrofitting in Spain. *Energy Policy, 130*(April), 375–388. https://doi.org/10.1016/j.enpol.2019.04.013
Osman, M. M., & Sevinc, H. (2019). Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan. *Sustainable Cities and Society, 47*(October 2017), Article 101429. https://doi.org/10.1016/j.scs.2019.101429
Parkinson, T., de Dear, R., & Brager, G. (2020). Nudging the adaptive thermal comfort model. *Energy and Buildings, 206*, Article 109559. https://doi.org/10.1016/j.enbuild.2019.109559
Ren, Z., & Chen, D. (2018). Modelling study of the impact of thermal comfort criteria on housing energy use in Australia. *Applied Energy, 210*(November 2017), 152–166. https://doi.org/10.1016/j.apenergy.2017.10.110
Roshan, G. R., Oji, R., & Attia, S. (2019). Projecting the impact of climate change on design recommendations for residential buildings in Iran. *Building and Environment, 155*(March), 283–297. https://doi.org/10.1016/j.buildenv.2019.03.053
Sánchez-García, D., Bienvenido-Huertas, D., Pulido-Arcas, J. A., & Rubio-Bellido, C. (2020). Analysis of energy consumption in different European cities: The adaptive comfort control implemented model (ACCIM) considering representative concentration pathways (RCP) scenarios. *Applied Sciences (Switzerland), 10*(4), 1–24. https://doi.org/10.3390/app10041513
Sánchez-García, D., Rubio-Bellido, C., Marrero Meléndez, M., Guevara-García, F. J., & Canivell, J. (2017). El control adaptativo en instalaciones existentes y su potencial en el contexto del cambio climático. *Hábitat Sustentable, 7*(4), 06–17.
Sánchez-García, D., Bienvenido-Huertas, D., Tristancho-Carvajal, M., & Rubio-Bellido, C. (2019). Adaptive Comfort Control Implemented Model (ACCIM) for energy consumption predictions in dwellings under current and future climate conditions: A case study located in Spain. *Energies, 12*(8), 1498. https://doi.org/10.3390/en12081498
Sánchez-García, D., Rubio-Bellido, C., del Río, J. J. M., & Pérez-Fargallo, A. (2019). Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change. *Energy and Buildings, 187*, 173–185. https://doi.org/10.1016/j.enbuild.2019.02.002
Sánchez-Guevara Sánchez, C., Mavrogianni, A., & Neila González, F. J. (2017). On the minimal thermal habitability conditions in low income dwellings in Spain for a new definition of fuel poverty. *Building and Environment, 114*, 344–356. https://doi.org/10.1016/j.buildenv.2016.12.029
Sánchez-Guevara Sánchez, C., Núñez Peiró, M., Taylor, J., Mavrogianni, A., & Neila González, J. (2019). Assessing population vulnerability towards summer energy poverty: Case studies of Madrid and London. *Energy and Buildings, 190*, 132–143. https://doi.org/10.1016/j.enbuild.2019.02.024
Sánchez-Guevara Sánchez, C., Sanz Fernández, A., Núñez Peiró, M., & Gómez Muñoz, G. (2020). Energy poverty in Madrid: Data exploitation at the city and district level. *Energy Policy, 144*(May). https://doi.org/10.1016/j.enpol.2020.111653
Scott, D., Hall, C. M., & Gossling, S. (2016). A review of the IPCC Fifth Assessment and implications for tourism sector climate resilience and decarbonization. *Journal of Sustainable Tourism, 24*(1), 8–30. https://doi.org/10.1080/09669582.2015.1062021
Seebauer, S. (2018). The psychology of rebound effects: Explaining energy efficiency rebound behaviours with electric vehicles and building insulation in Austria. *Energy Research and Social Science, 46*(March), 311–320. https://doi.org/10.1016/j.erss.2018.08.006
Semprini, G., Gulli, R., & Ferrante, A. (2017). Deep regeneration vs shallow renovation to achieve nearly Zero Energy in existing buildings: Energy saving and economic impact of design solutions in the housing stock of Bologna. *Energy and Buildings, 156*, 327–342. https://doi.org/10.1016/j.enbuild.2017.09.044
Shortt, N., & Rugkåsa, J. (2007). "The walls were so damp and cold" fuel poverty and ill health in Northern Ireland: Results from a housing intervention. *Health and Place, 13*(1), 99–110. https://doi.org/10.1016/j.healthplace.2005.10.004
Siksnelyte-Butkiene, I., Streimikiene, D., Lekavicius, V., & Balezentis, T. (2021). Energy poverty indicators: A systematic literature review and comprehensive analysis of integrity. *Sustainable Cities and Society, 67*. https://doi.org/10.1016/j.scs.2021.102756
Spanish Institute of Statistics. (2011). *Census of population and housing (2011)*. https://www.ine.es/censos2011_datos/cen11_datos_resultados.htm.
Steenbergen, R. D. J. M., Koster, T., & Geurts, C. P. W. (2012). The effect of climate change and natural variability on wind loading values for buildings. *Building and Environment, 55*, 178–186. https://doi.org/10.1016/j.buildenv.2012.03.010
Tabata, T., & Tsai, P. (2020). Fuel poverty in Summer: An empirical analysis using microdata for Japan. *Science of the Total Environment, 703*, Article 135038. https://doi.org/10.1016/j.scitotenv.2019.135038
Tarekegne, B. (2020). Just electrification: Imagining the justice dimensions of energy access and addressing energy poverty. *Energy Research and Social Science, 70* (November 2019), Article 101639. https://doi.org/10.1016/j.erss.2020.101639
Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society, 93*(4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1
The Government of Spain. (1979). *Royal Decree 2429/79. Approving the basic building norm NBE-CT-79, about the thermal conditions in buildings*. In Normas básicas de la edificación.
The Government of Spain. (2006). *Royal Decree 314/2006. Approving the Spanish technical building code*.
The Government of Spain. (2014). *Royal Decree 216/2014, of 28 March, sets out the methodology for the calculation of the Voluntary Price for the Small Consumer*.
The Government of Spain. (2019). *National Strategy against energy poverty 2019–2024 (Spain)*.
Thomson, H., & Snell, C. (2013). Quantifying the prevalence of fuel poverty across the European Union. *Energy Policy, 52*, 563–572. https://doi.org/10.1016/j.enpol.2012.10.009
Tirado Herrero, S., Jiménez Meneses, L., López Fernández, J. L., Perero Van Hove, E., Irigoyen Hidalgo, V. M., & Savary, P. (2016). *Pobreza, vulnerabilidad y desigualdad energética. Nuevos enfoques de análisis*. Madrid: Asociación de Ciencias Ambientales.
Udrea, I., Croitoru, C., Nastase, I., Crutescu, R., & Badescu, V. (2018). First adaptive thermal comfort equation for naturally ventilated buildings in Bucharest, Romania. *International Journal of Ventilation, 17*(3), 149–165. https://doi.org/10.1080/14733315.2017.1356057
Ürge-Vorsatz, D., & Tirado Herrero, S. (2012). Building synergies between climate change mitigation and energy poverty alleviation. *Energy Policy, 49*, 83–90. https://doi.org/10.1016/j.enpol.2011.11.093
Verichev, K., Zamorano, M., & Carpio, M. (2020). Effects of climate change on variations in climatic zones and heating energy consumption of residential buildings in the southern Chile. *Energy and Buildings, 215*, Article 109874. https://doi.org/10.1016/j.enbuild.2020.109874
Vilches, A., Barrios Padura, Á., & Molina Huelva, M. (2017). Retrofitting of homes for people in fuel poverty: Approach based on household thermal comfort. *Energy Policy, 100*(October 2016), 283–291. https://doi.org/10.1016/j.enpol.2016.10.016
Williamson, T., & Daniel, L. (2020). A new adaptive thermal comfort model for homes in temperate climates of Australia. *Energy and Buildings, 210*, Article 109728. https://doi.org/10.1016/j.enbuild.2019.109728
Xu, P., Huang, Y. J., Miller, N., Schlegel, N., & Shen, P. (2012). Impacts of climate change on building heating and cooling energy patterns in California. *Energy, 44*(1), 792–804. https://doi.org/10.1016/j.energy.2012.05.013
Yassaghi, H., Mostafavi, N., & Hoque, S. (2019). Evaluation of current and future hourly weather data intended for building designs: A Philadelphia case study. *Energy and Buildings, 199*, 491–511. https://doi.org/10.1016/j.enbuild.2019.07.016
Yun, G. Y., Lee, J. H., & Steemers, K. (2016). Extending the applicability of the adaptive comfort model to the control of air-conditioning systems. *Building and Environment, 105*, 13–23. https://doi.org/10.1016/j.buildenv.2016.05.027
Zhai, Z. J., & Helman, J. M. (2019). Implications of climate changes to building energy and design. *Sustainable Cities and Society, 44*(June 2018), 511–519. https://doi.org/10.1016/j.scs.2018.10.043